PRISM

Development of FFAG ring for muon phase-space rotation

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BNL Seminar

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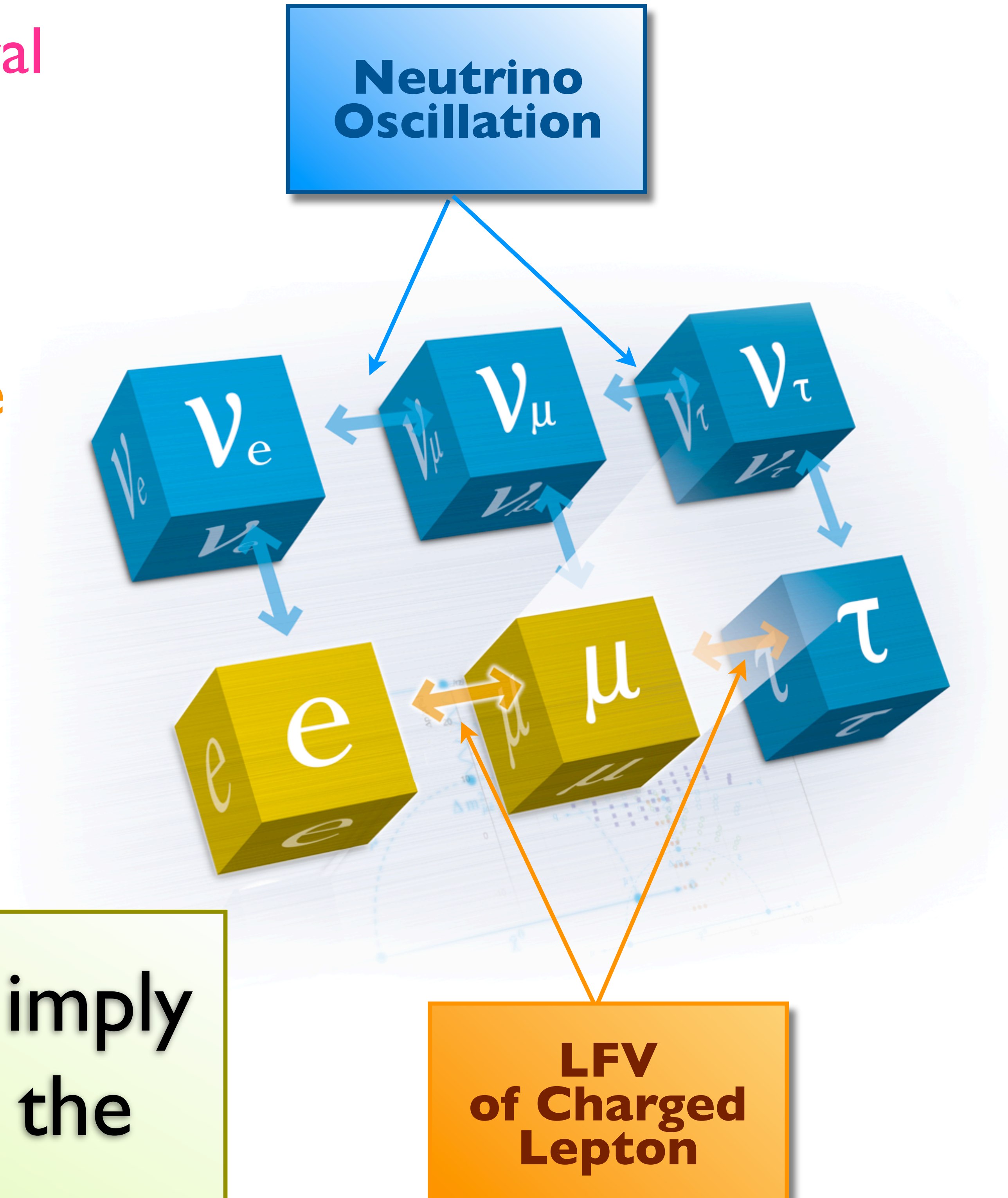
Physics Motivation

Lepton Flavor Violation : LFV

- Lepton flavor violation of neutral lepton : Observed. (Neutrino oscillation)
- Lepton flavor violation of charged lepton (LFV) : Yet to be observed.
- c-LFV will be occurred by neutrino mixing, but branching ratio is too small ($\sim 10^{-54}$) to observe.

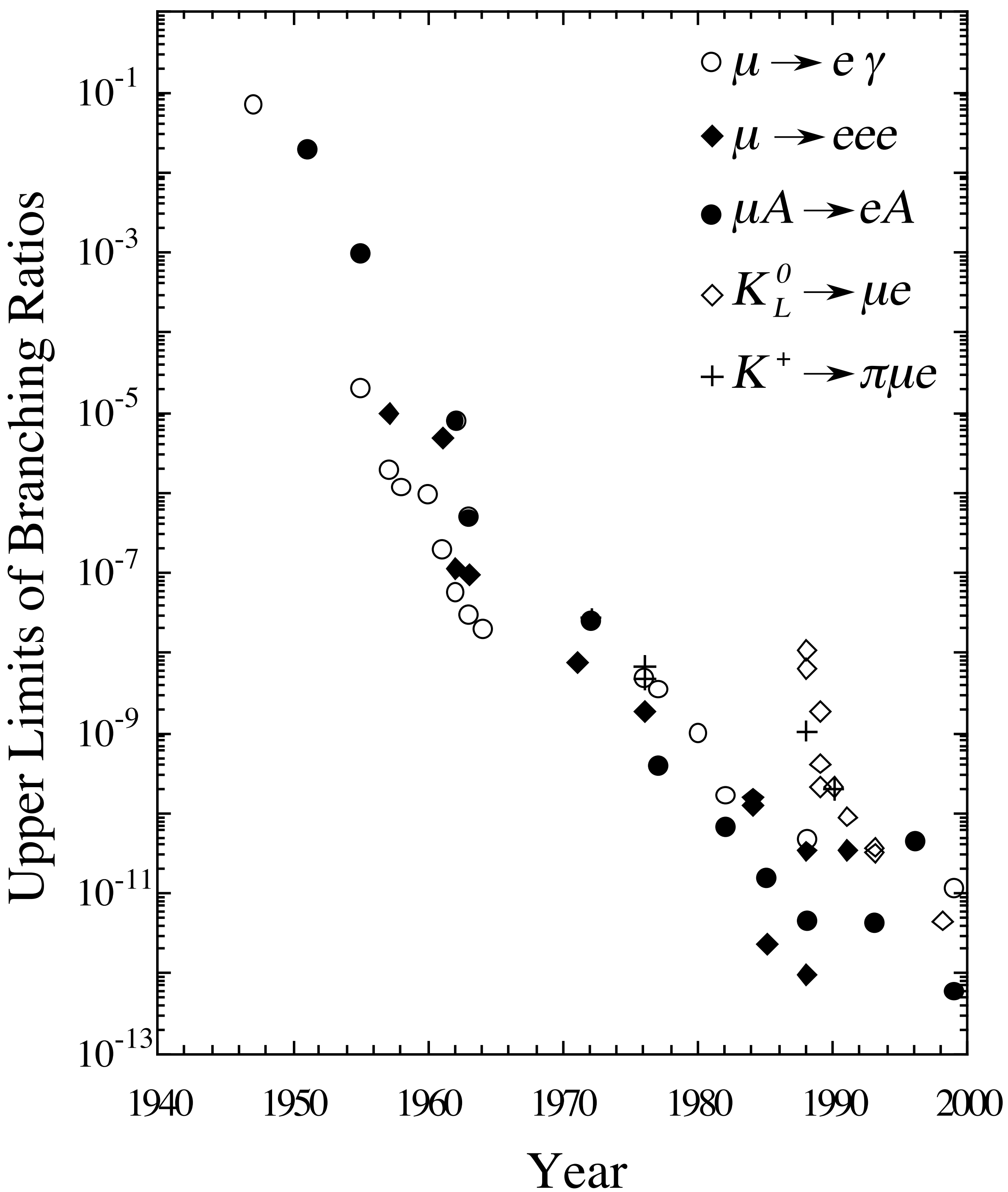


Discovery of **LFV** would imply "***new physics***" beyond the Standard Model

History of Experimental Search for LFV

- Upper limits are improved by two order in decade.
- Sensitivity of muon-LFV are the highest.
- It can be obtained intense muon beam than other particle such as kaon.

Muon is suitable particle for the LFV search.

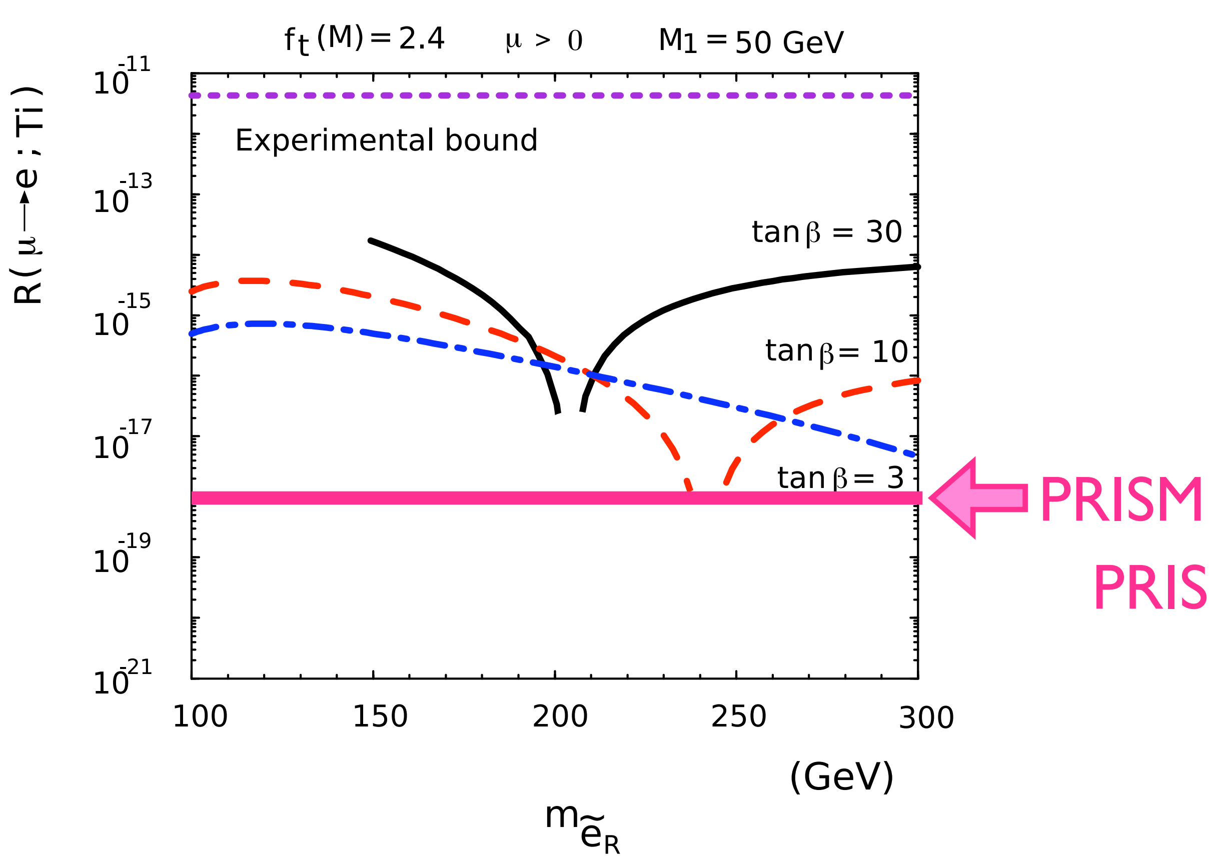


History of LFV Search limits

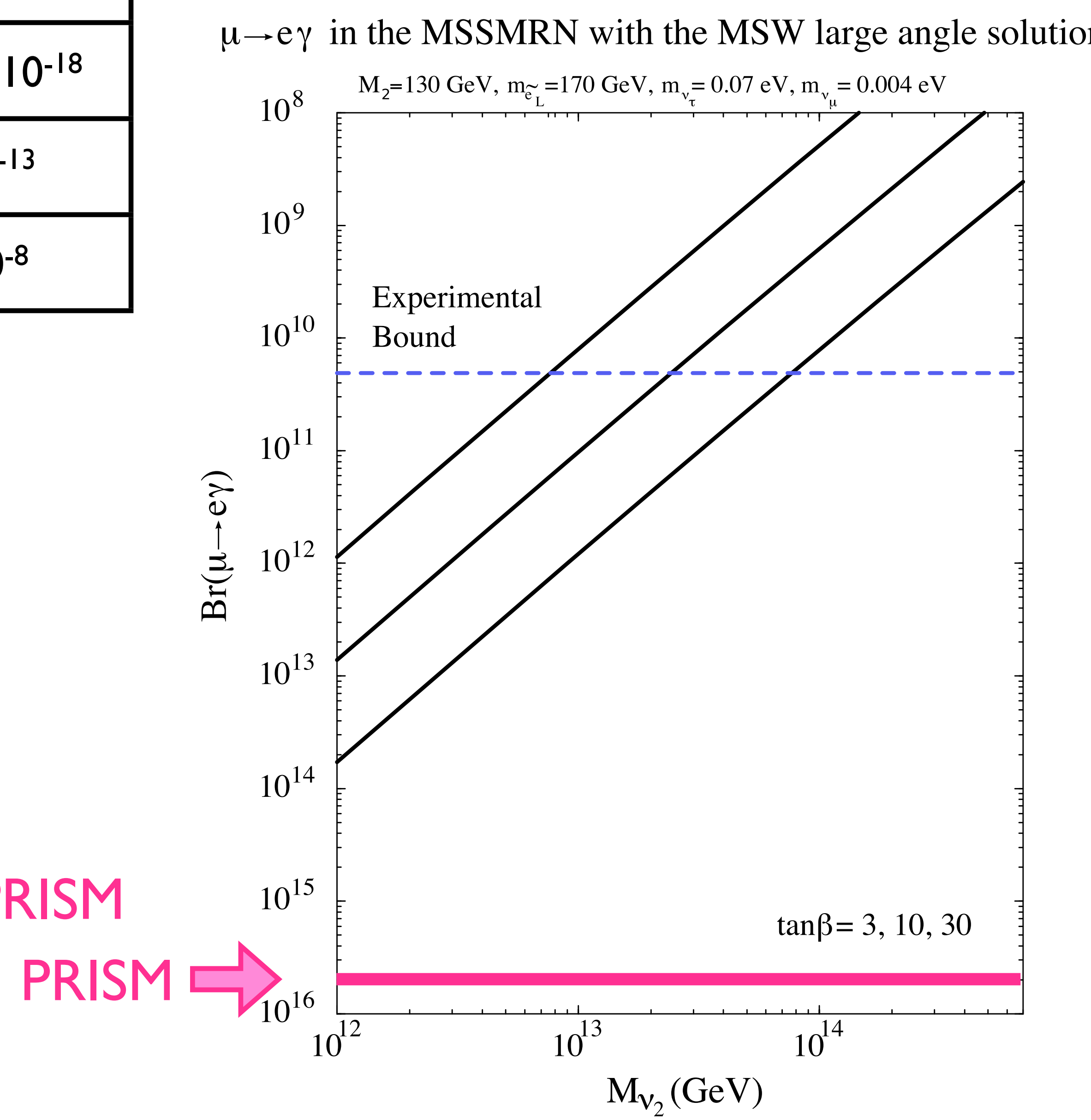
Theoretical Prediction

Process	Current Limit	SUSY-GUT Level	Future
$\mu N \to e N$	10^{-13}	10^{-16}	$10^{-16}, 10^{-18}$
$\mu \to e \gamma$	10^{-11}	10^{-14}	10^{-13}
$\tau \to \mu \gamma$	10^{-6}	10^{-9}	10^{-8}

SUSY-GUT

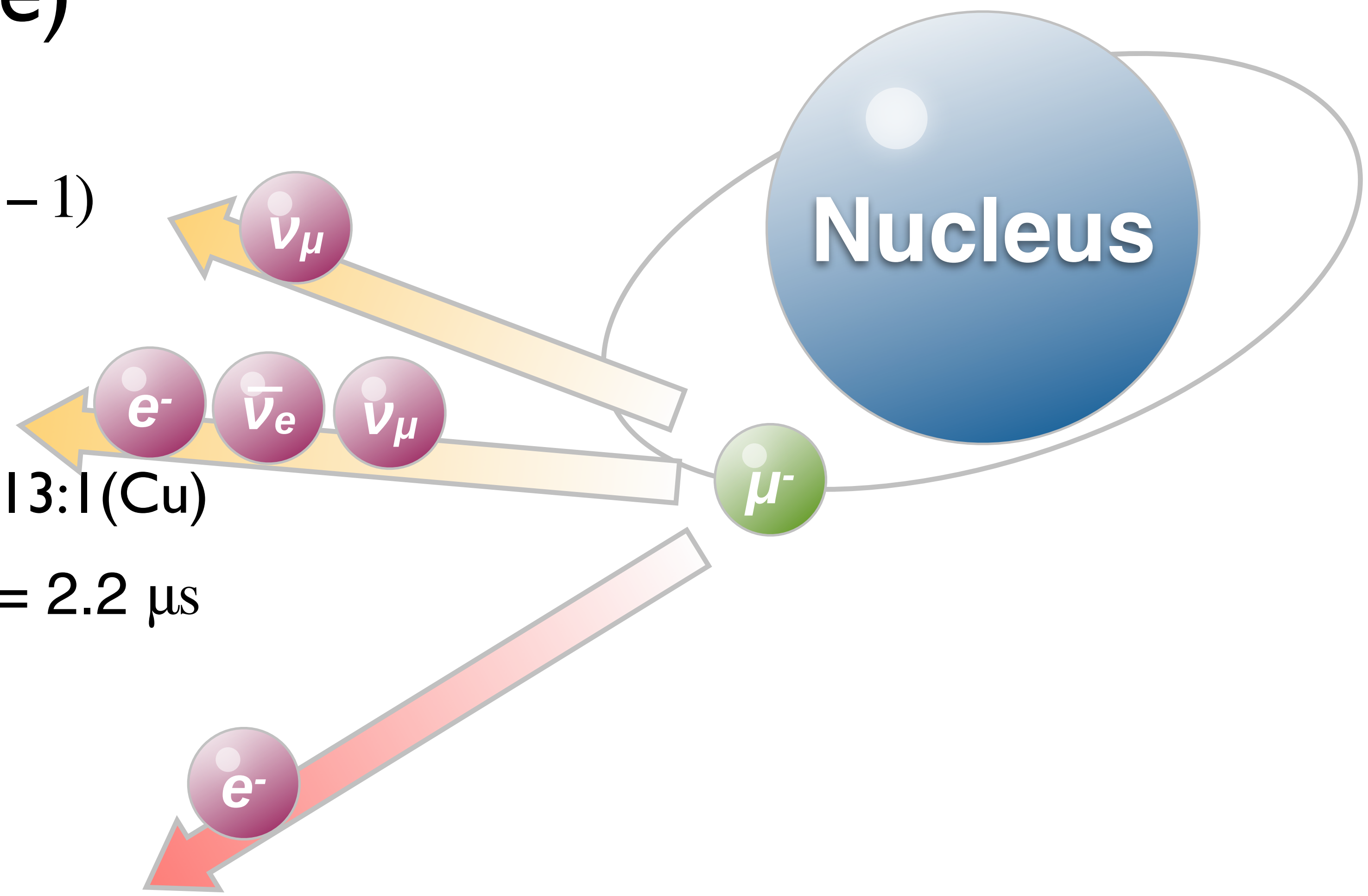


SUSY+Seesaw, MSW Large Angle



μ-e Conversion

- **Muonic Atom (1S state)**
  - Muon Capture (MC)
    - $\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$
  - Muon Decay in Orbit (MDO)
    - $\mu^- \rightarrow e^- \nu \bar{\nu}$
  - MC:MDO = 1:1000(H), 3:2(Al), 13:1(Cu)
  - $\tau(\mu^-;\mathrm{Al})$ = 0.88 μs; $\tau(\text{free-}\mu^-)$ = 2.2 μs
- **μ-e Conversion**
  - $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$
  - Coherent Process

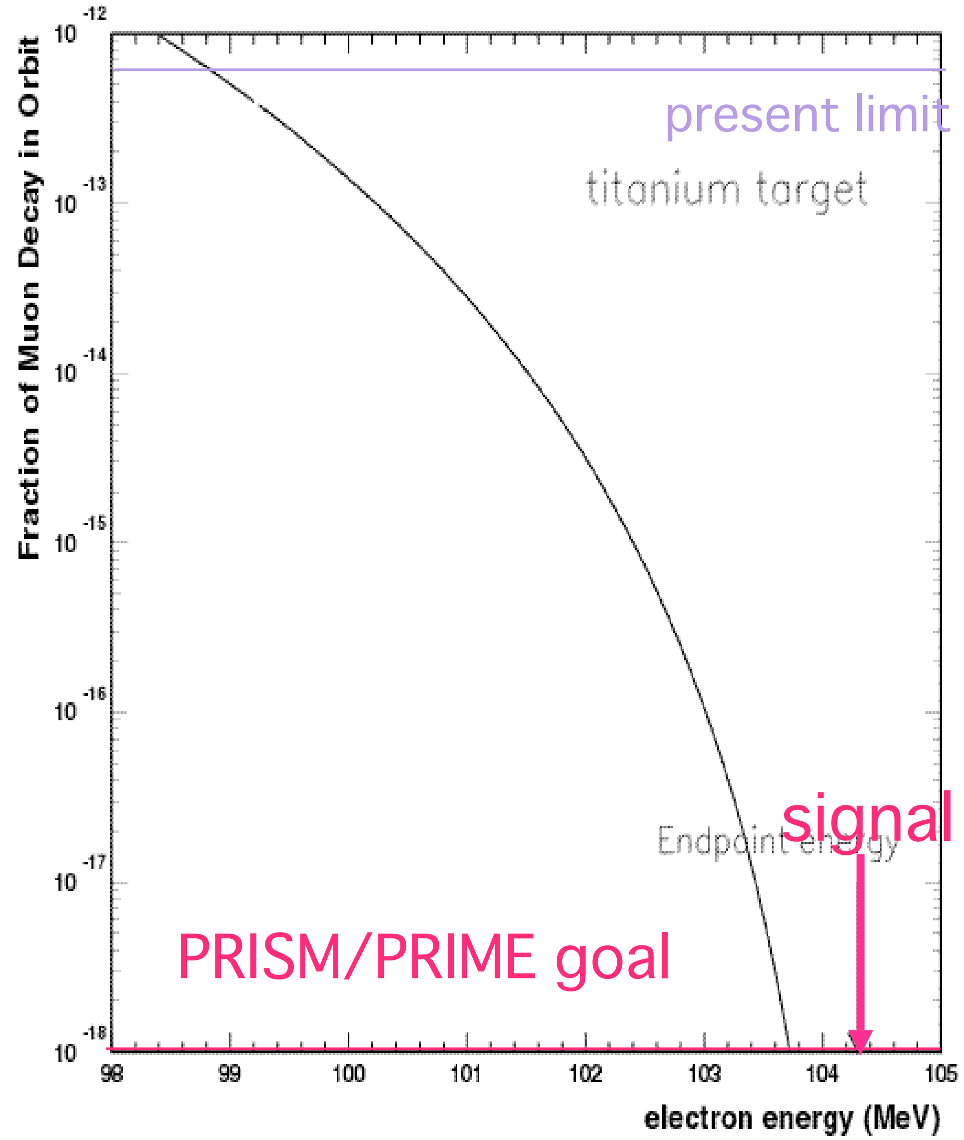


$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

Signal from mu-e conversion

- Conversion in 1s orbit
  - $E_e > 103.9$ MeV
  - $\Delta E_e = 350$ keV
  - $N_{BG} \sim 0.17$ @ $R=10^{-18}$

Energy spectrum



Required muon beam for μ-e conversion experiment

- Higher muon intensity
  - more than 10^{12} μ-/sec
- Pulsed beam
  - rejection of background from proton beam
- Narrow energy spread
  - allow a thinner muon-stopping target
  - better e^- resolution and acceptance
- Less beam contamination
  - no pion contamination
    - long flight path
  - beam extinction between pulses
    - kicker magnet

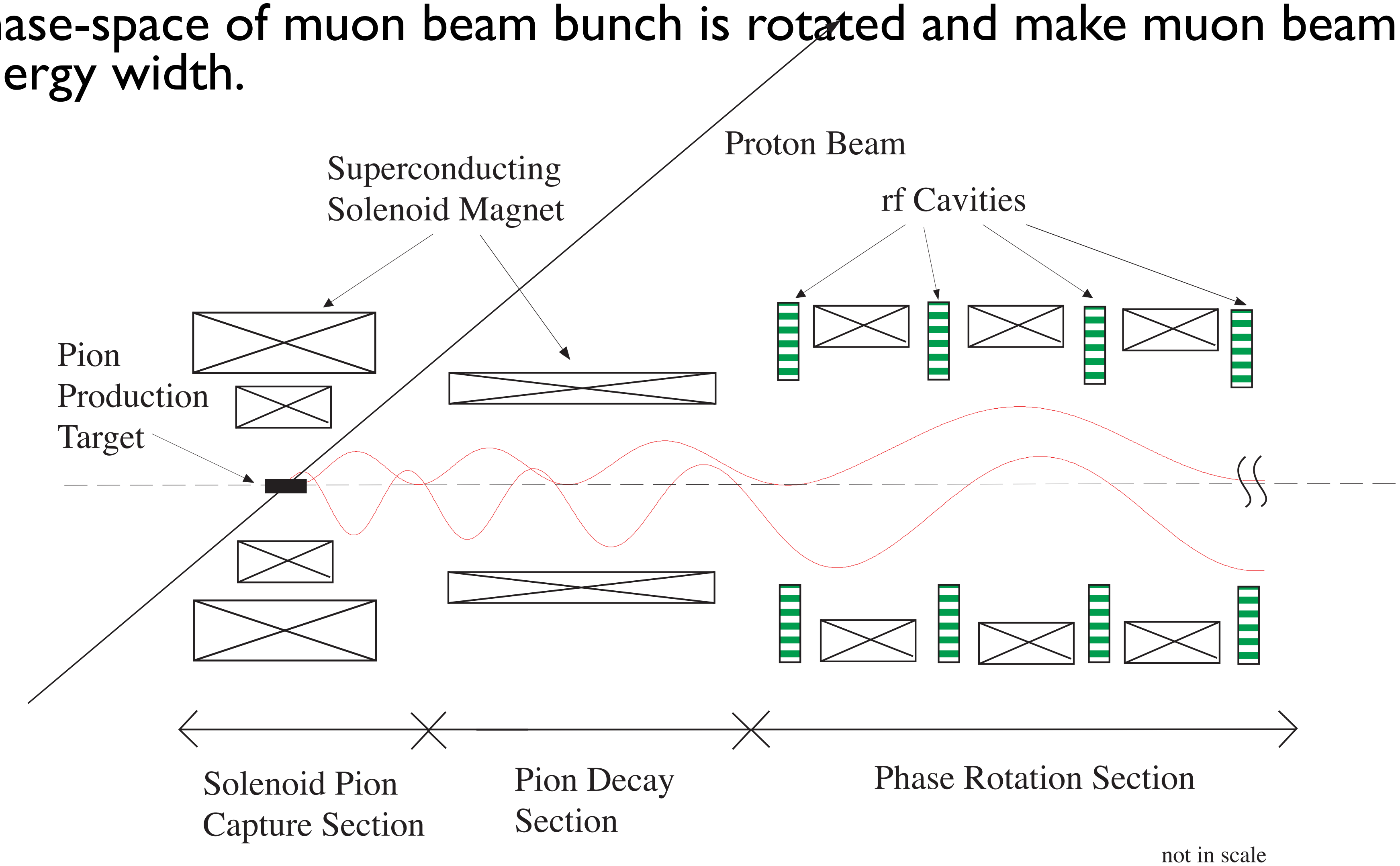
PRISM Project

PRISM Project

- PRISM = Phase Rotated Intense Slow Muon source
- Search for Lepton Flavor Violation
  - $N + \mu^- \to N + e^-$
  - Signal sensitivity : $\sim 10^{-18}$
- Muon beam intensity: $10^{11} \sim 10^{12}$ μ^-/sec
- Energy spread : ±2 %

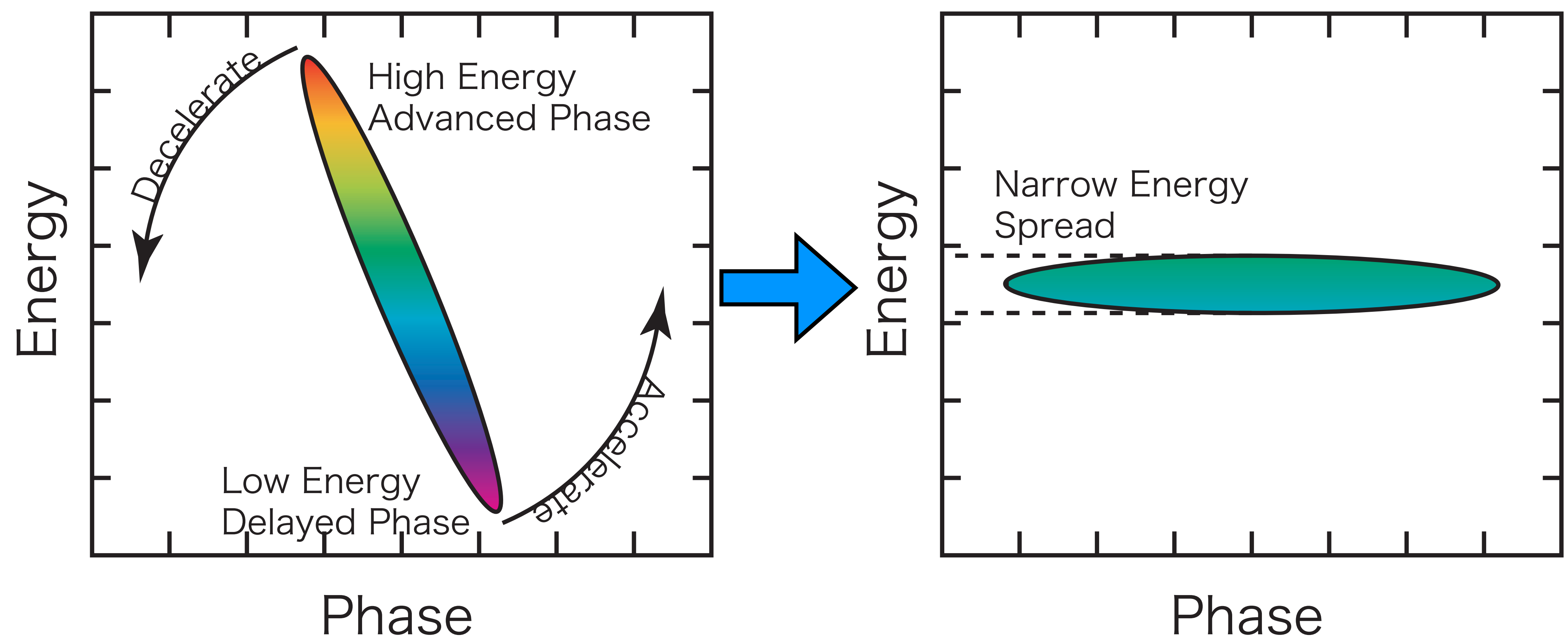
PRISM Scheme

- Pion Capture Section
  - Pions are produced and captured with a solenoidal magnet.
- Pion Decay and Muon Transport Section
  - Pions decay into muons and the muons are transported with a solenoidal magnet.
- Phase Rotation Section
  - Phase-space of muon beam bunch is rotated and make muon beam of narrow energy width.



What is Phase Rotation ?

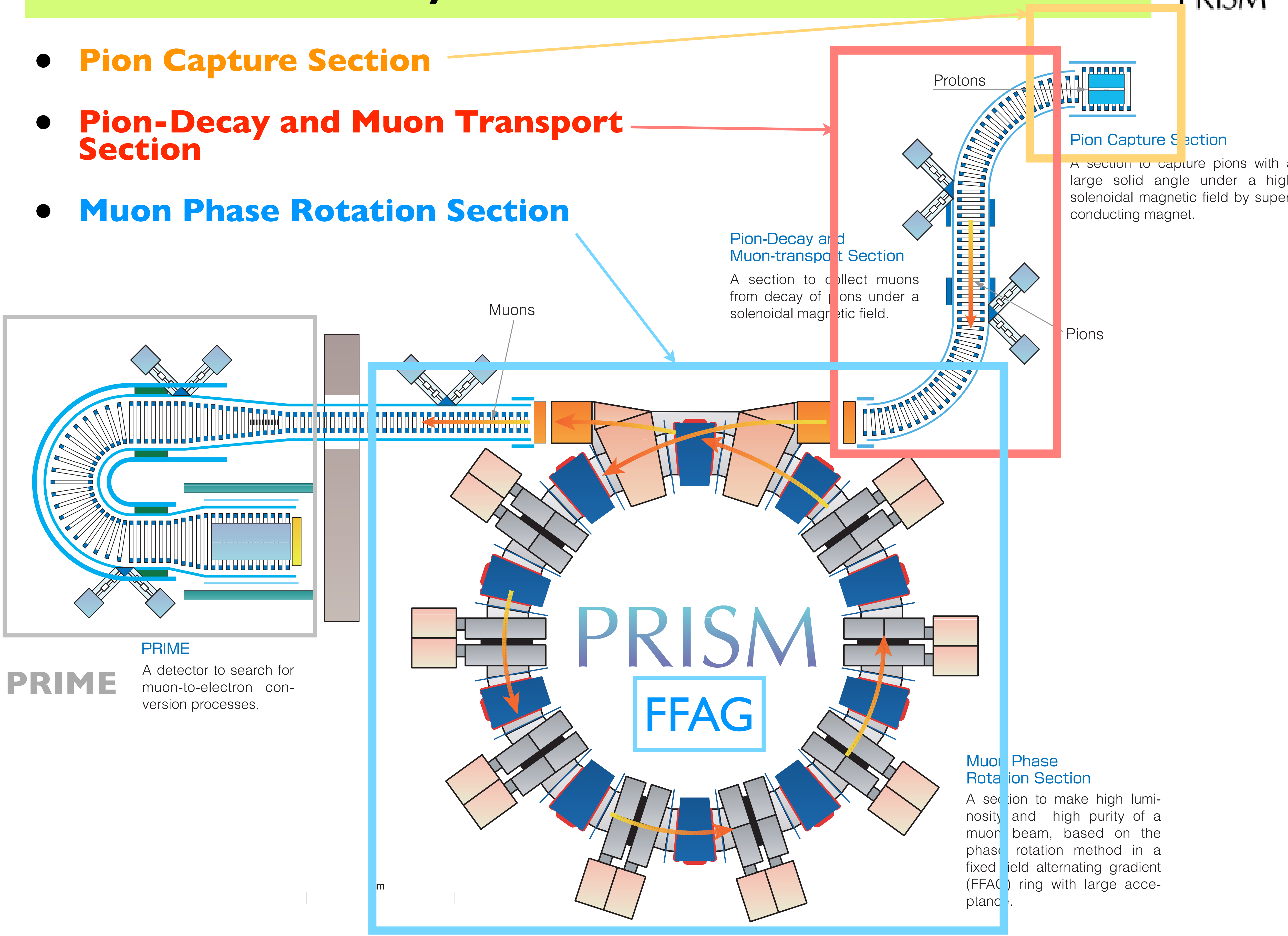
- Beam bunch is rotated in ϕ-ΔE phase space by applying an RF field.
- The RF field accelerate slow muons and decelerate fast muons.



Principle of Phase Rotation

Layout of PRISM

- **Pion Capture Section**
- **Pion-Decay and Muon Transport Section**
- **Muon Phase Rotation Section**



Phase-Space Rotator:
PRISM-FFAG Ring

Requirement for Phase Rotator

- Synchrotron Oscillation
  - Phase-space rotation by RF cavity.
- Rapid Phase Rotation
  - Shuld be done within muon liftime, 2.2 usec.
- Storage Ring
  - Reduction of Number of RF cavity
- Large momentum acceptance
- Large transverse acceptance

Fixed Field Alternating Gradient Synchrotron

Types of FFAG accelerator

PRISM

- Scaling FFAG Adopted for PRISM
  - Consist of high gradient non-linear magnets.

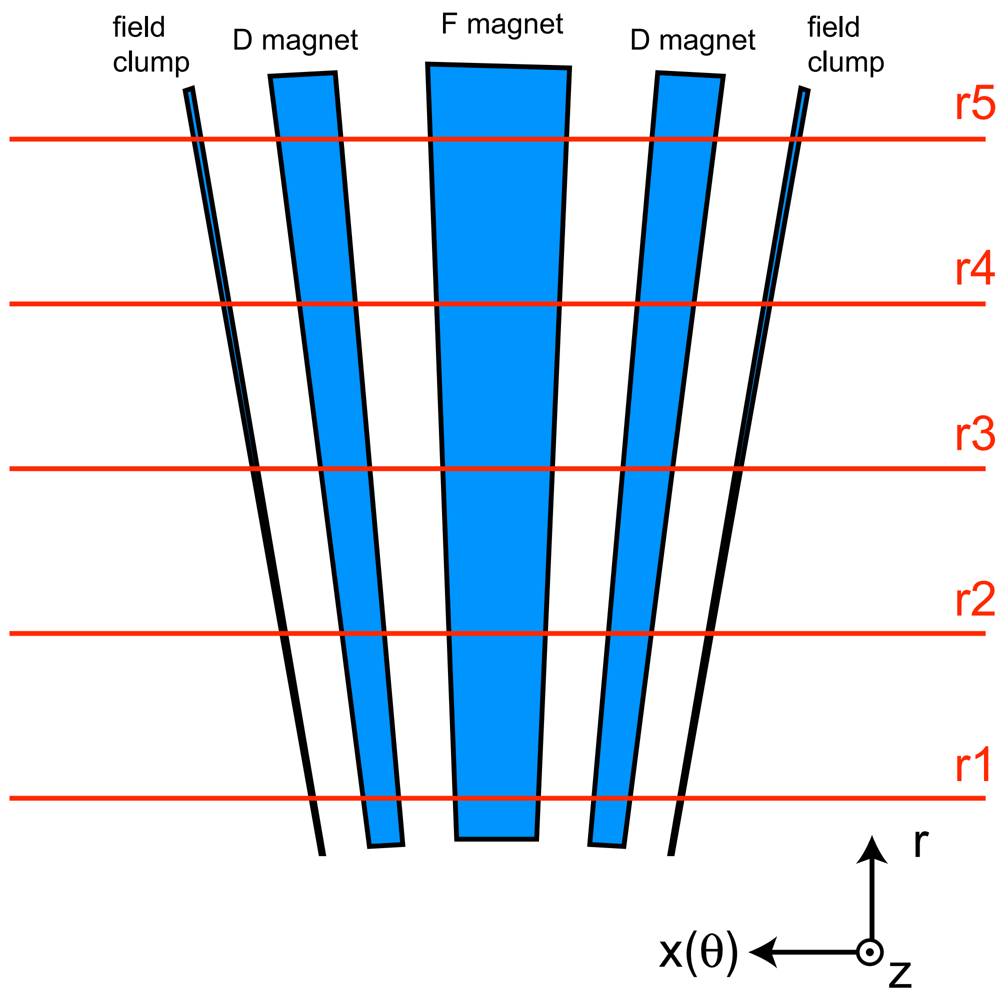
    * $B(r) = B_0 \left(\frac{r}{r_0}\right)^k$

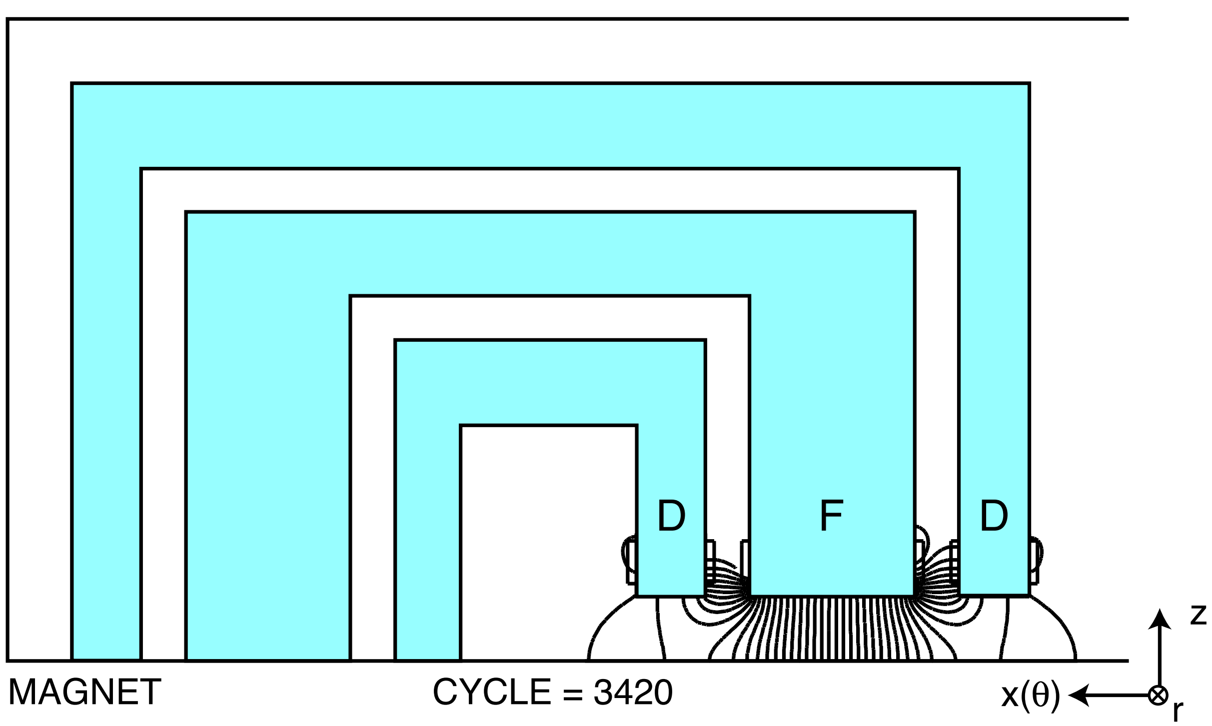
  - Tunes does not change with different momentum.
  - Acceleration of proton beam has been succeded by small machin. (KEK : PoP FFAG)
- Non-Scaling FFAG
  - Consist of conventional (linear) magnets (dipole and Q magnets).
  - Tunes change with different momentum.

Lattice Design

Method of Lattice Design

- Lattice design requires tracking with 3 D magnetic field map.
- It takes a long time to produce 3D magnetic field.
- 3D magnetic field reproduced by interpolating 2D magnetic field.

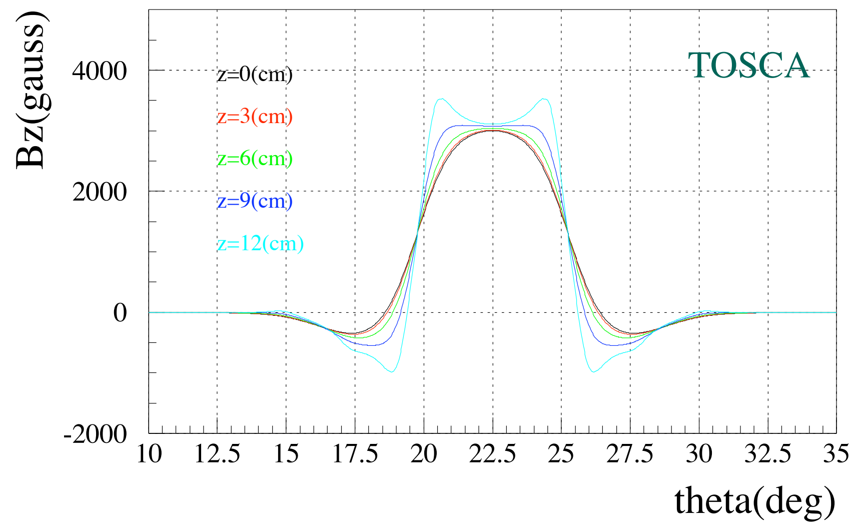


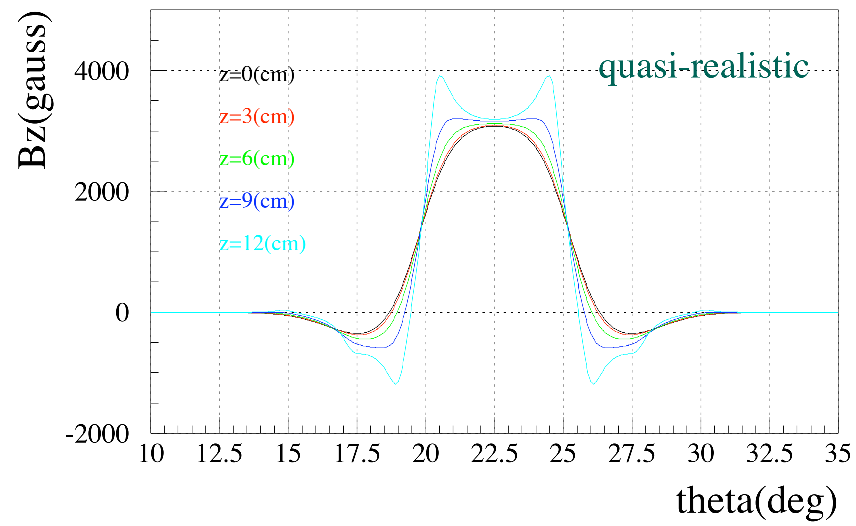


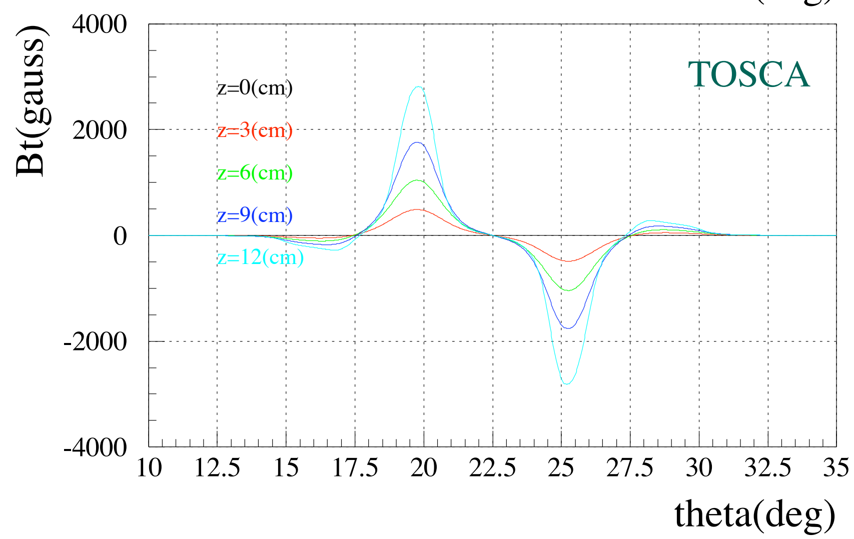
Comparison of B field

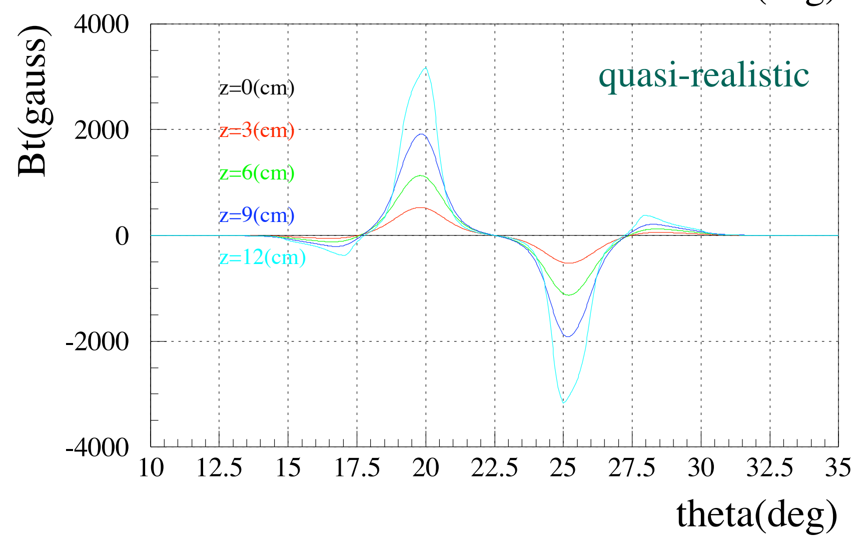
TOSCA

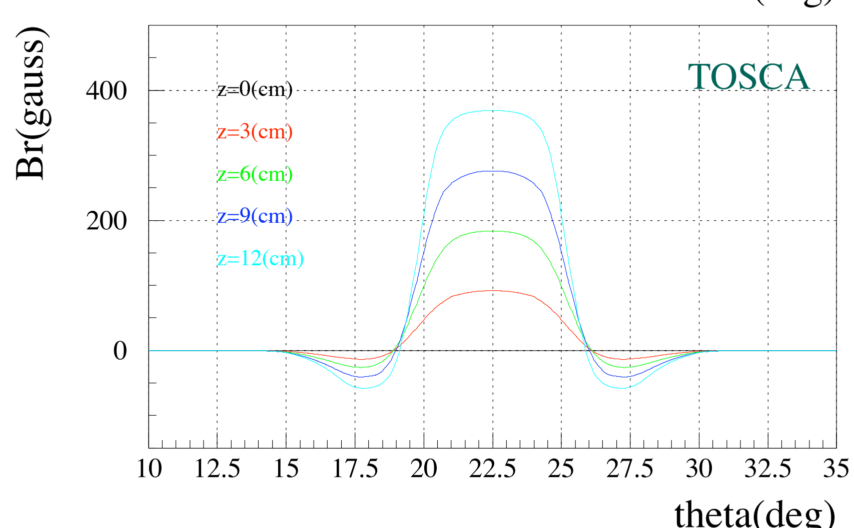
quasi-realistic

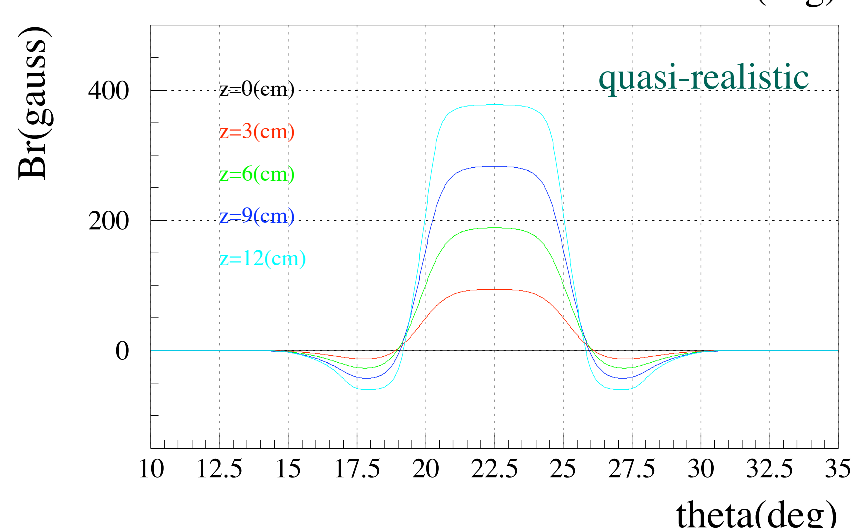










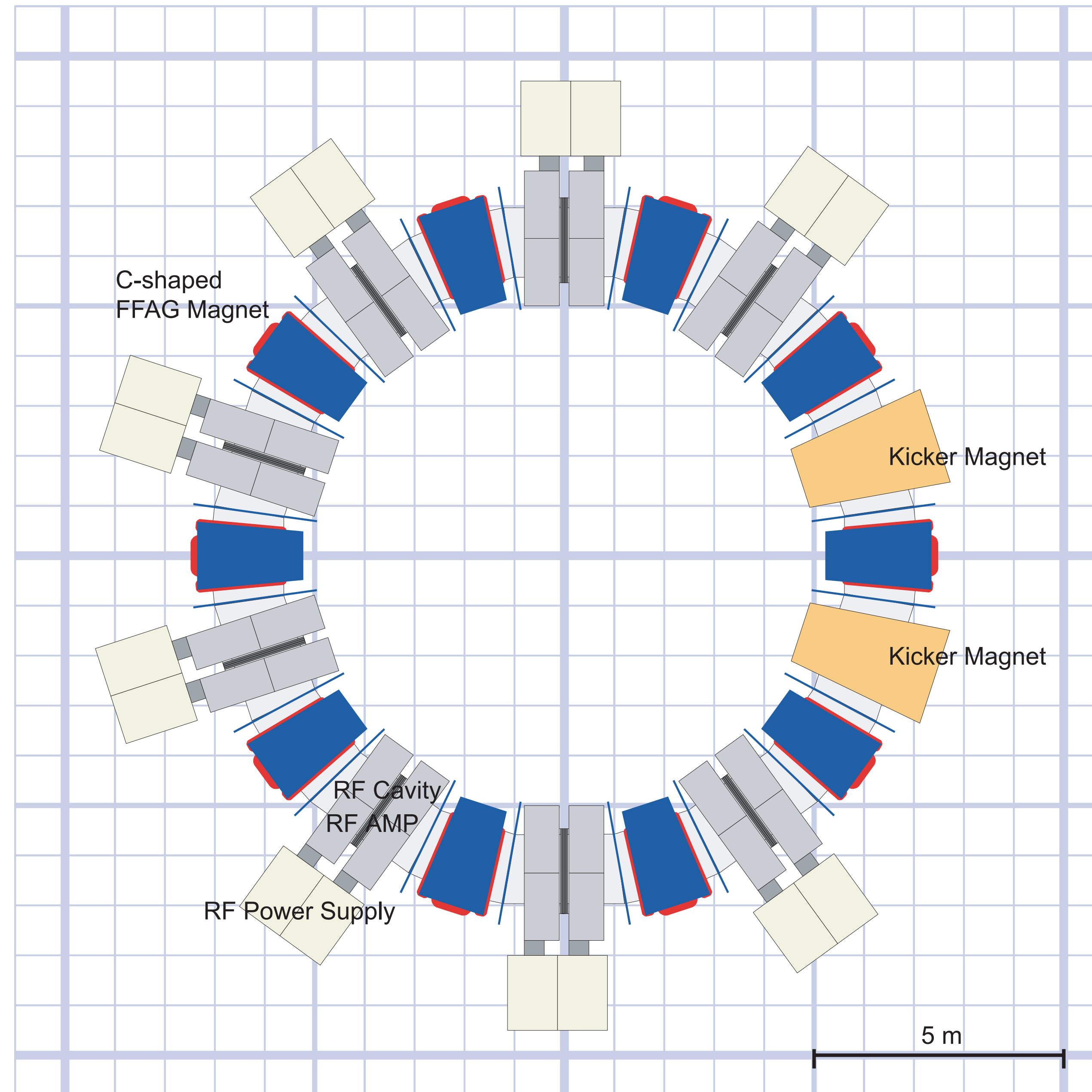


> 8 hours

several min.!

PRISM-FFAG Lattice

- Scaling FFAG
- Radial sector DFD triplet
- Number of cells : 10
- Field index (k value) : 4.6
- Bending (Focus/Defocus) ratio : 6.0
- Momentum : 68 MeV/c ± 20 %
- Equilibrium radius : 6.5 m



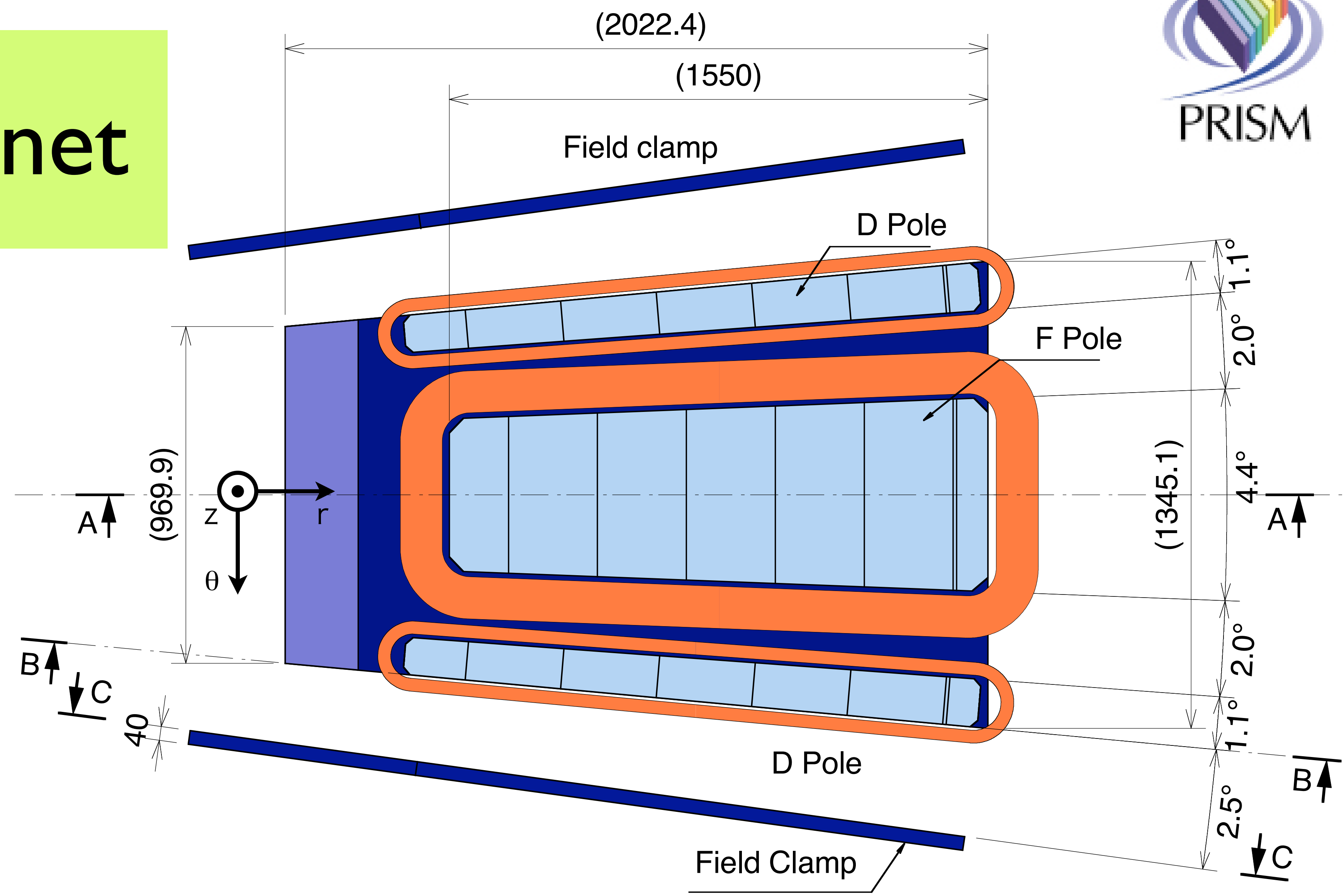
Magnet Design

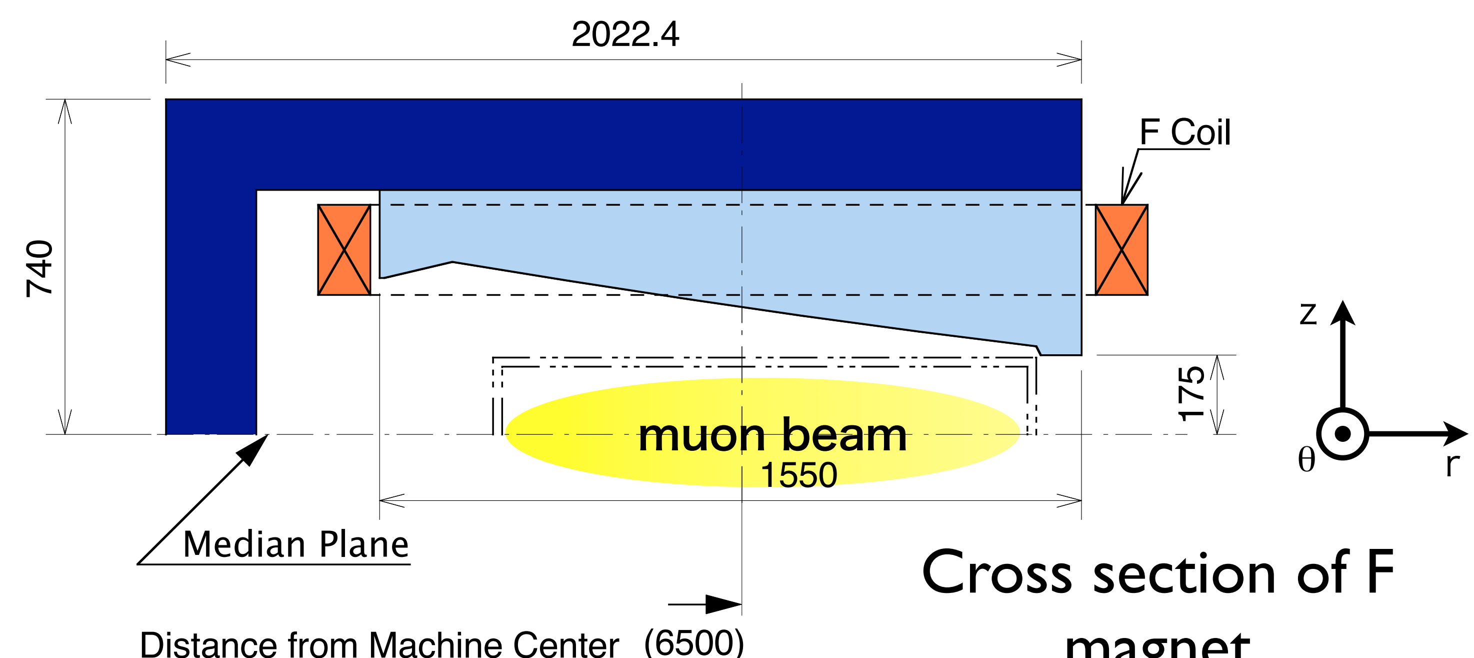
Requirement for PRISM-FFAG Magnet

- Large momentum acceptance
  - $\Delta p = \pm 20$ % at 68 MeV/c
- Large transverse acceptance
  - horizontal : 20,000 pi mm mrad
  - vertical : 3,000 pi mm mrad
- Compact magnet
  - Length along beam axis is ~ 1.5 m

PRISM-FFAG Magnet

- Scaling type
- DFD triplet
- Aperture
  - 100 cm (horizontal)
  - 30 cm (vertical)
- Thin Shape
  - Length along beam axis : ~1.2 m
- Designed by 3D magnet design code, TOSCA





Cross section of F magnet

Tracking simulation : Phase Space Distribution

$P = 68\ \mathrm{MeV}/c$ Beam duct height = ± 15 cm

Horizontal phase space

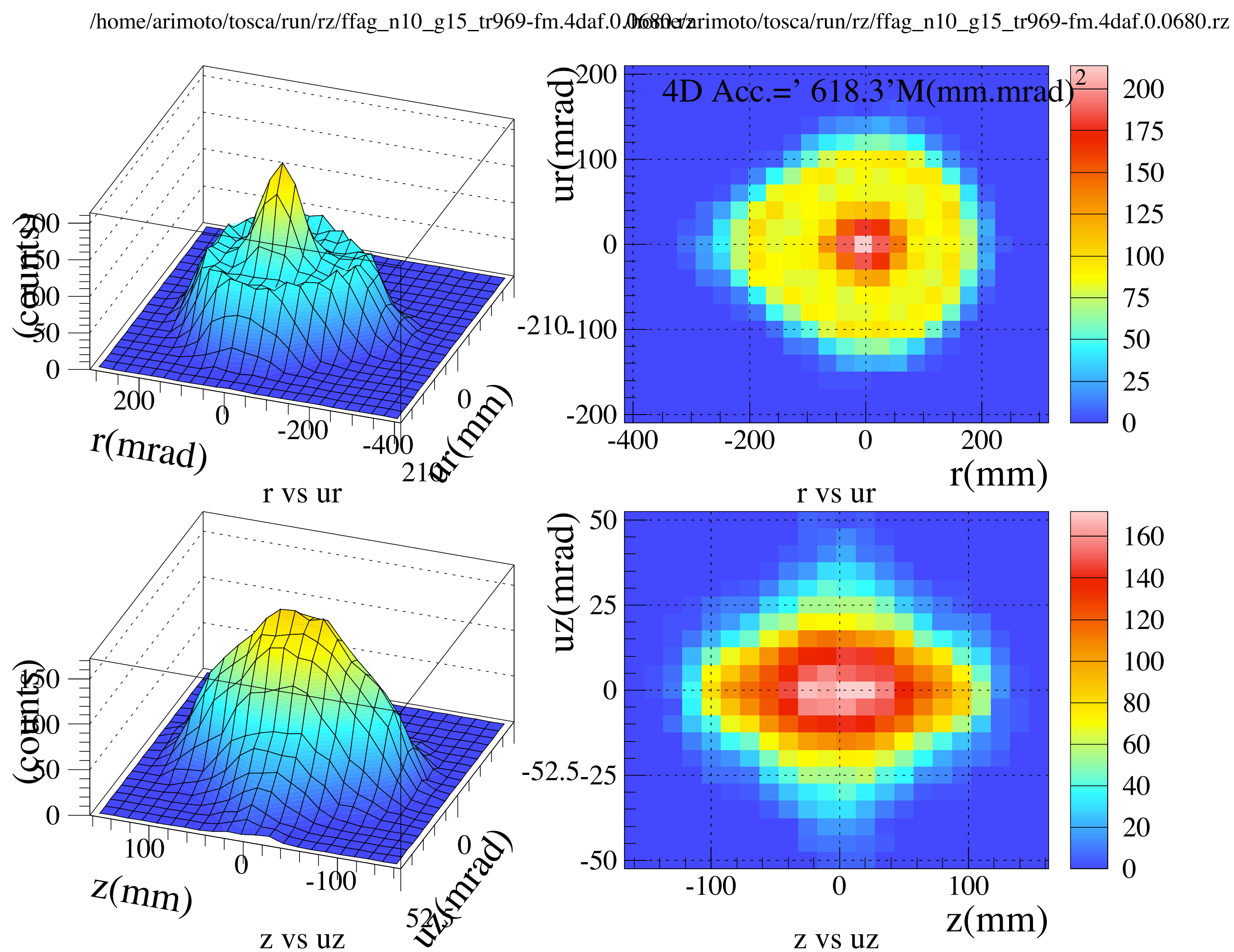
(@center of straight section)

38000 pi mm mrad

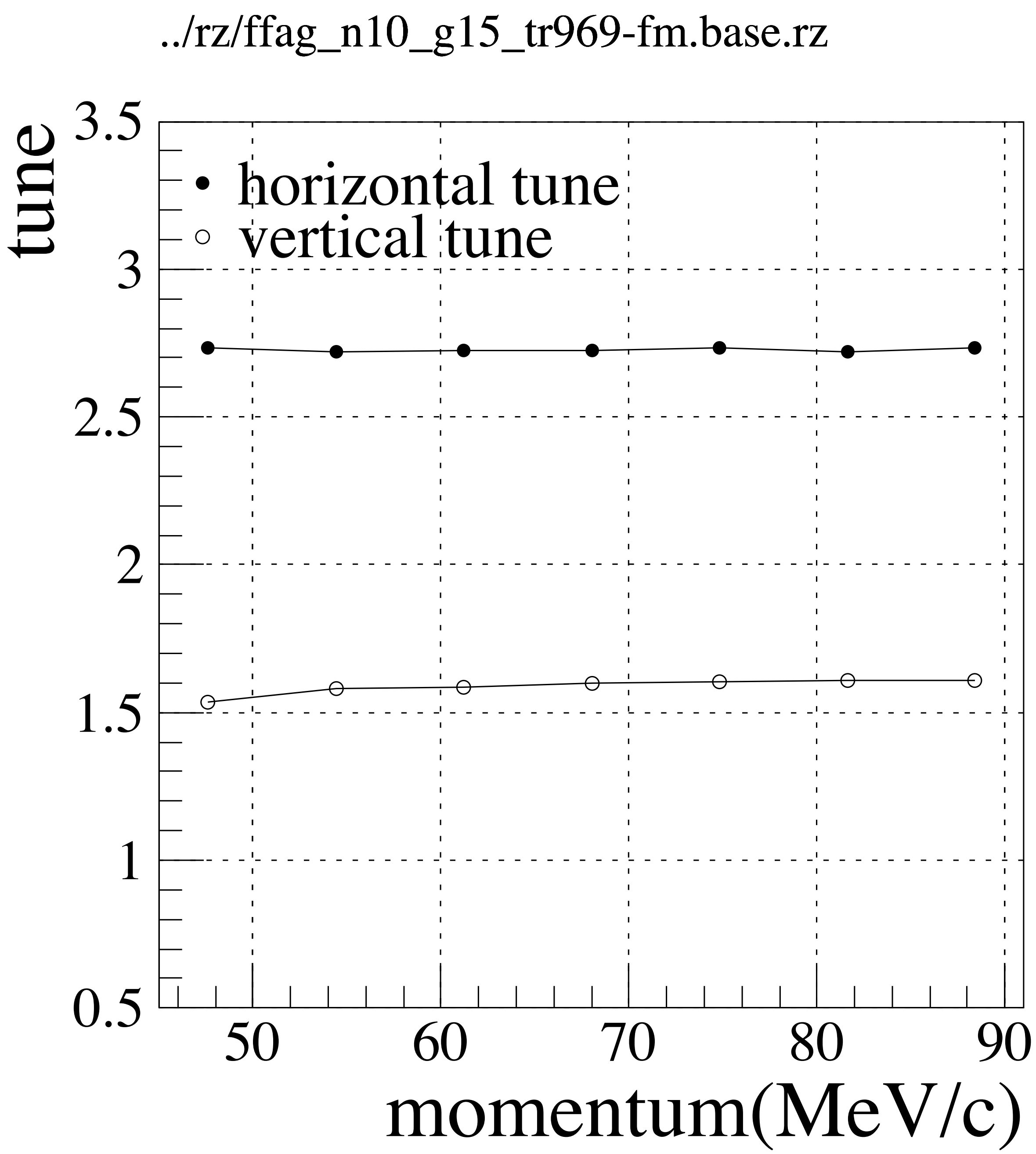
Vertical phase space

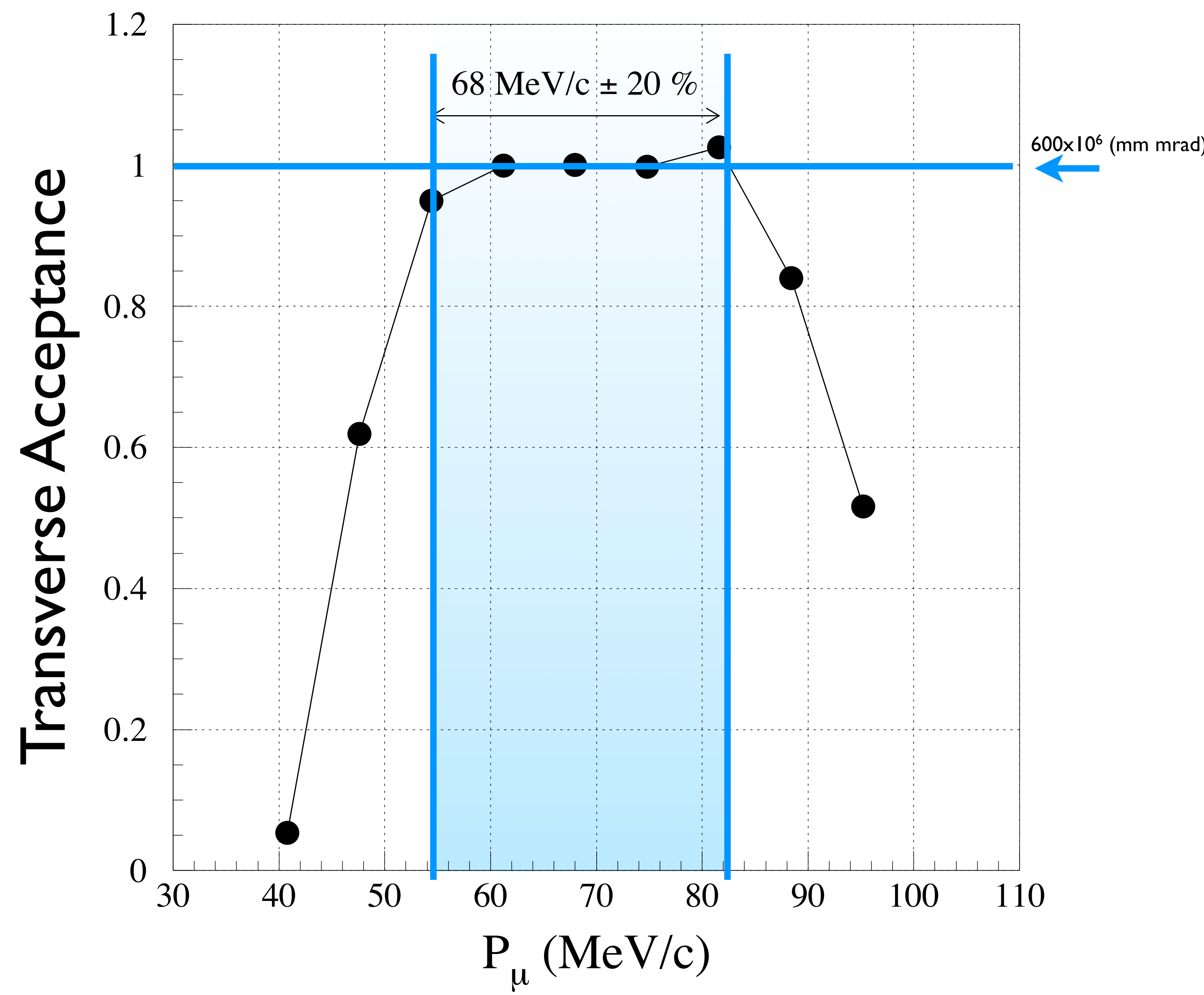
(@center of straight section)

6000 pi mm mrad



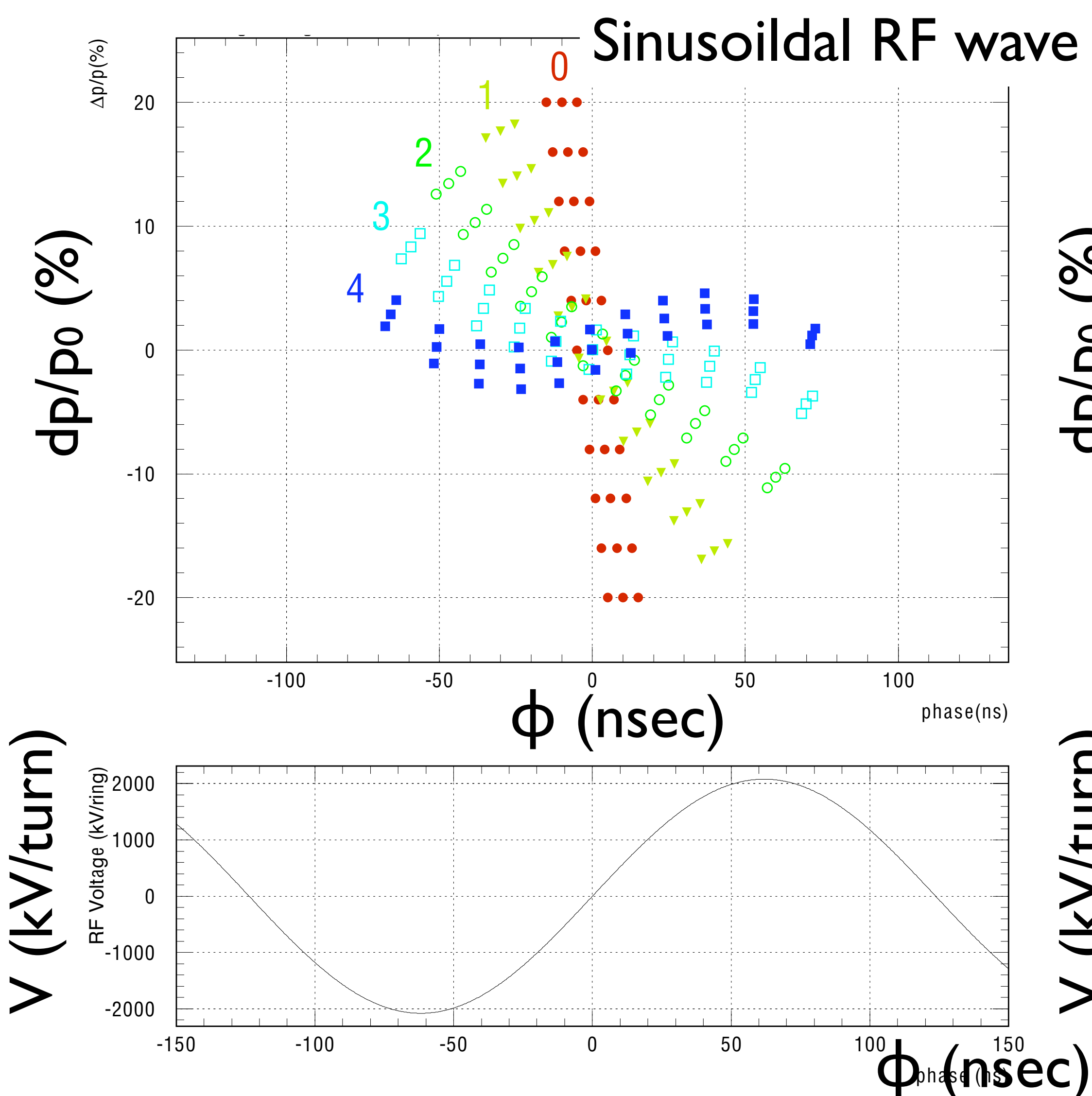
Zero Chromaticity



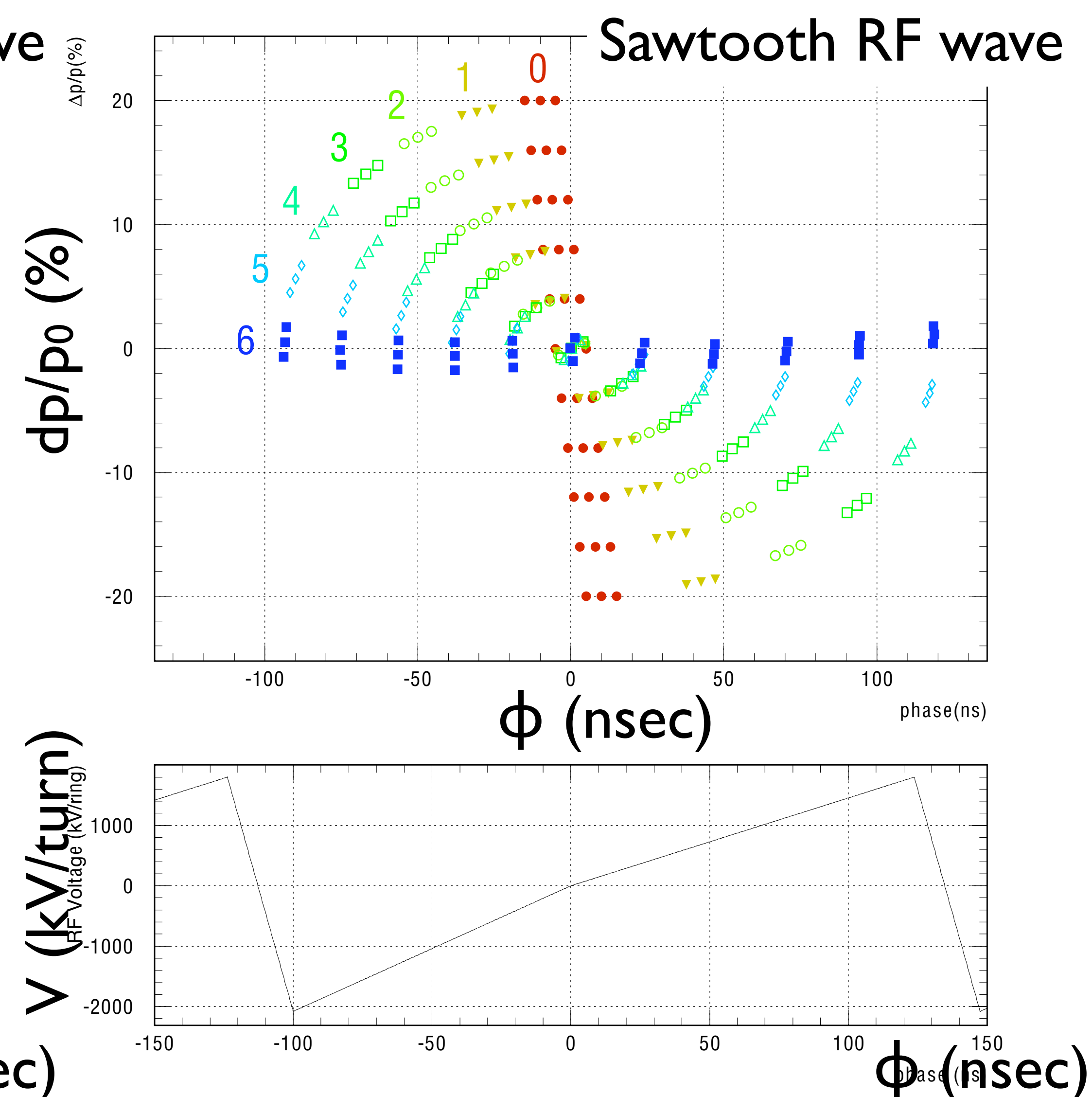


Phase-Space Rotation

Simulation of Phase-Space Rotation



$\Delta p/p$: 4%
num. of turn : 4
time : 1.0μs
μ survival rate : 68%



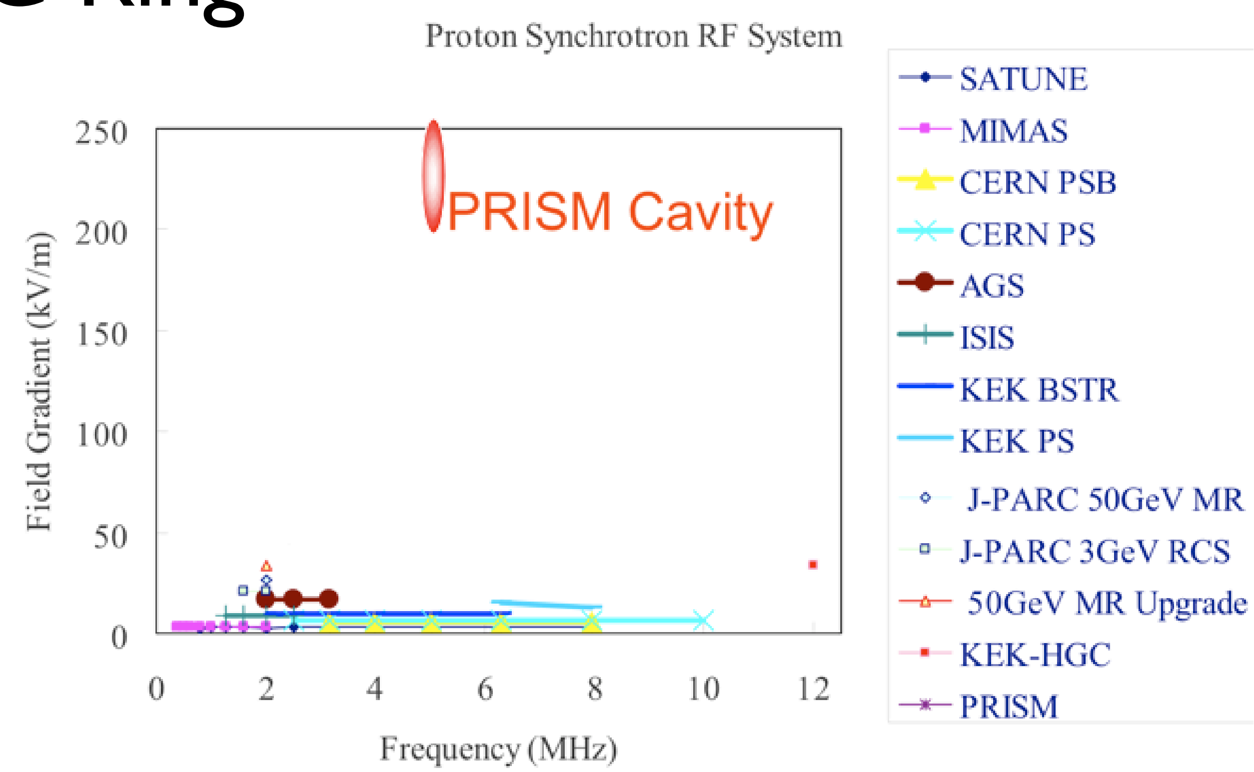
$\Delta p/p$: 2%
num. of turn : 6
time : 1.5μs
μ survival rate : 56%

- Sawtooth RF wave is nessesary.

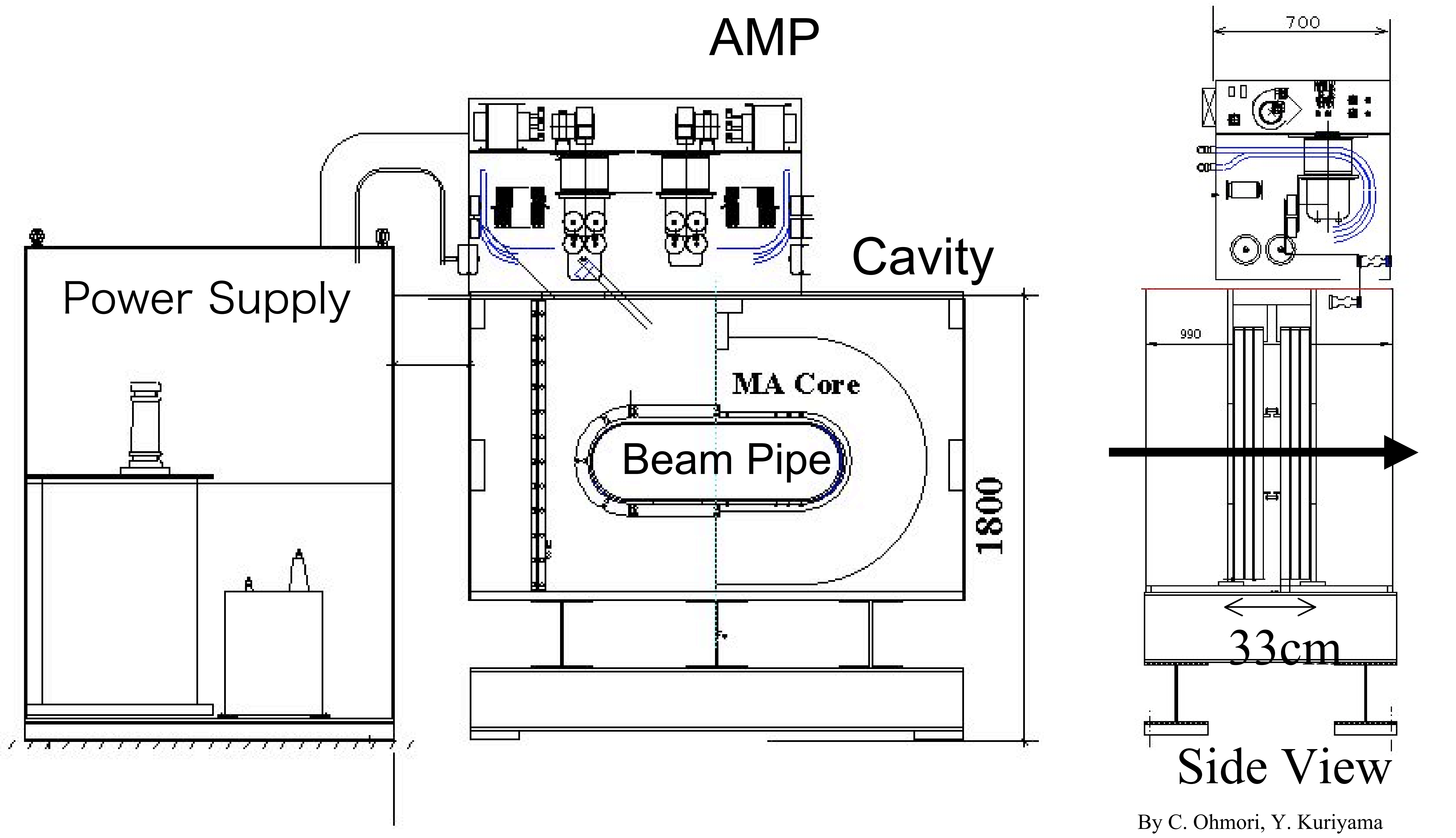
R&D of components

RF System

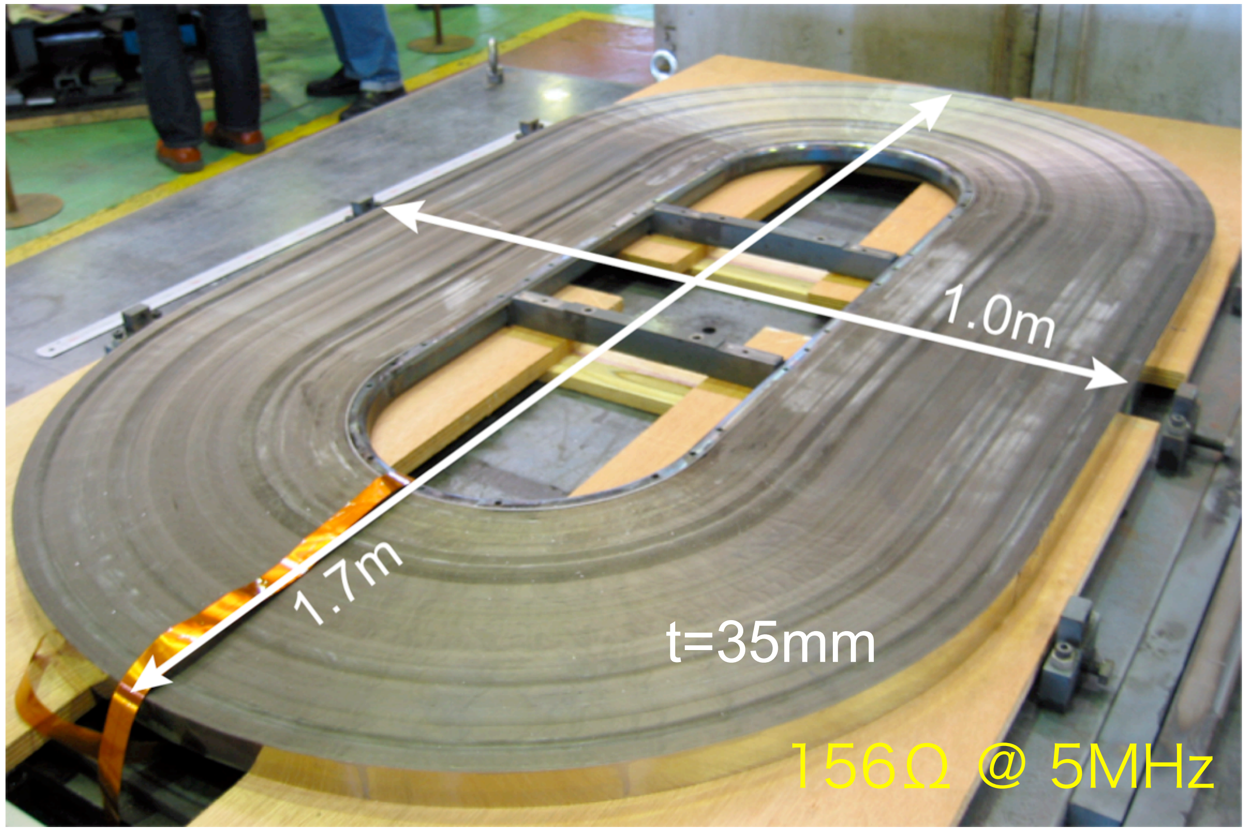
- Field gradient ~ 200 kV/m @ 5 MHz
- Duty : 0.1 %
- RF core material : Magnetic arroy (FINEMET)
- RF core size: 1 m (h) x 1.7 m (w) x 0.35 m (t)
- Six RF cavity sections in FFAG Ring
  - 5 Gap per one RF cavity



PRISM-RF System

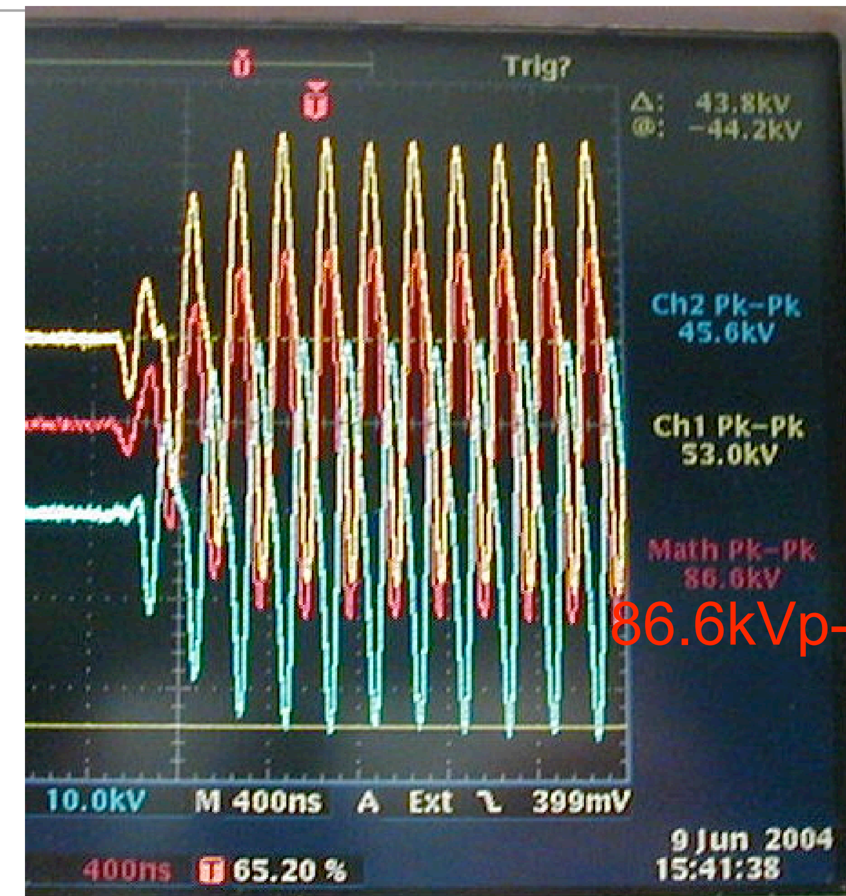


RF Cavity for PRISM-FFAG



Magnetic Alloy : FINEMET

RF AMP R&D

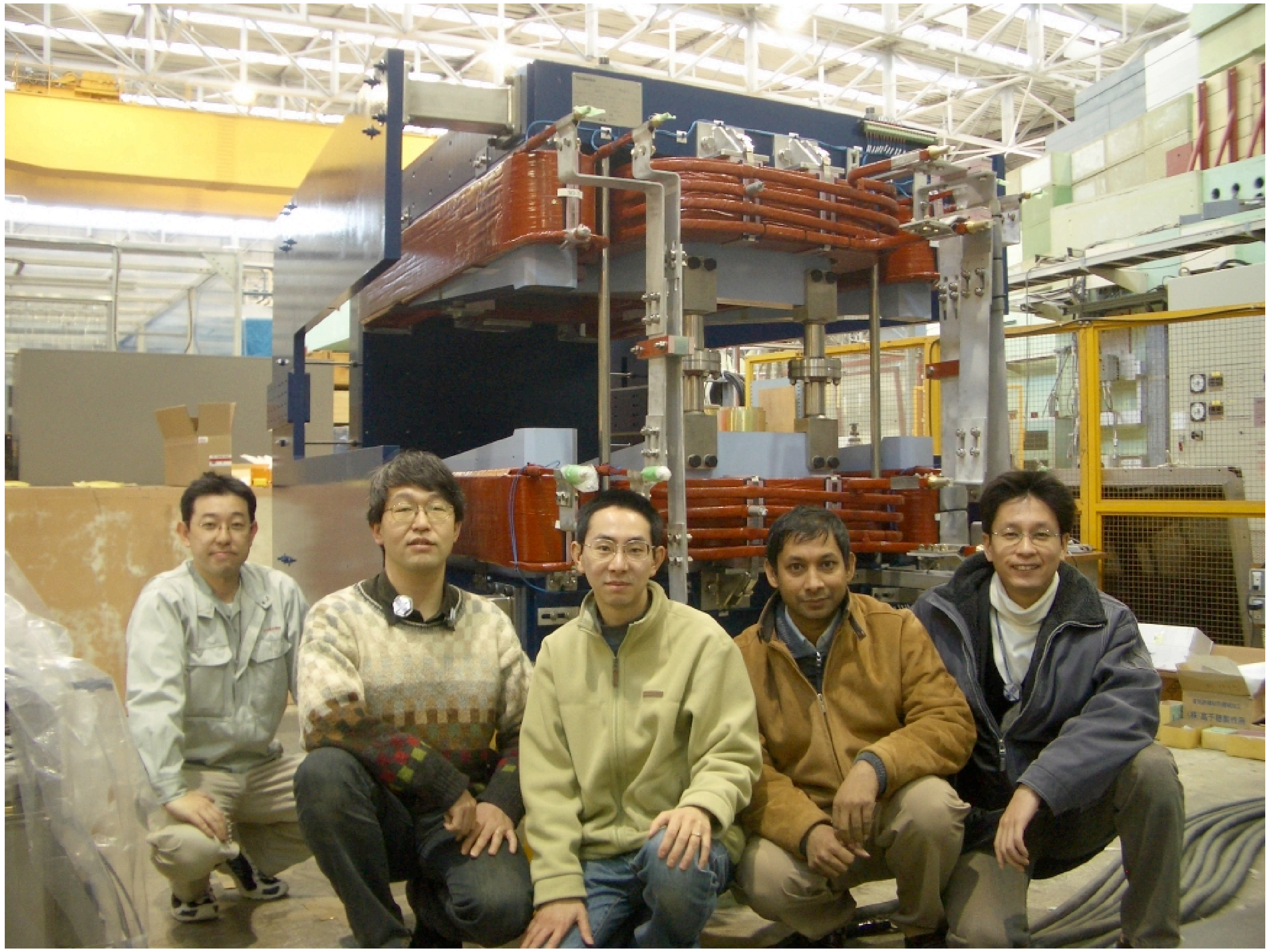


43kV/gap
w/ 734Ω dummy cavity
@5MHz

expected gradient
w/ PRISM-cavity (954Ω)
56kV_gap = 170kV/m

PRISM-FFAG Magnet

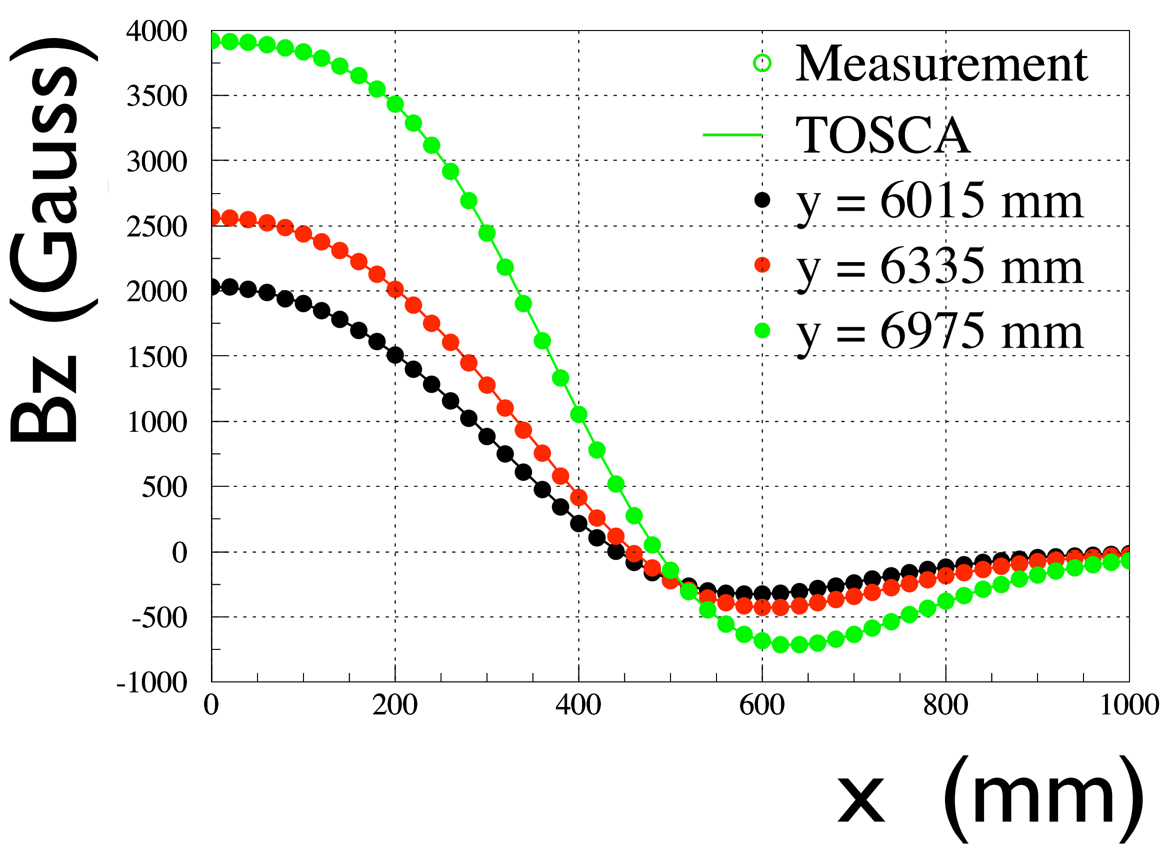
- Six magnets have been produced.
- Magnet measurements for three magnets have been finished.

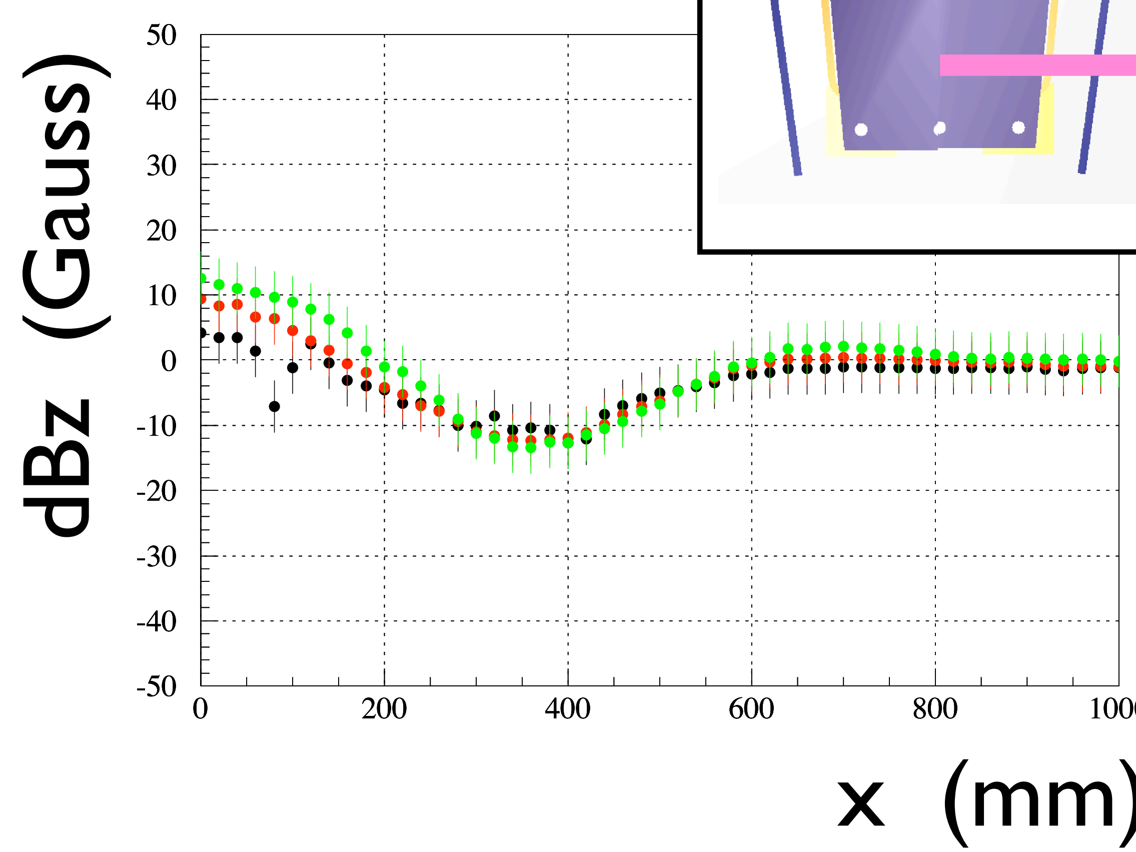


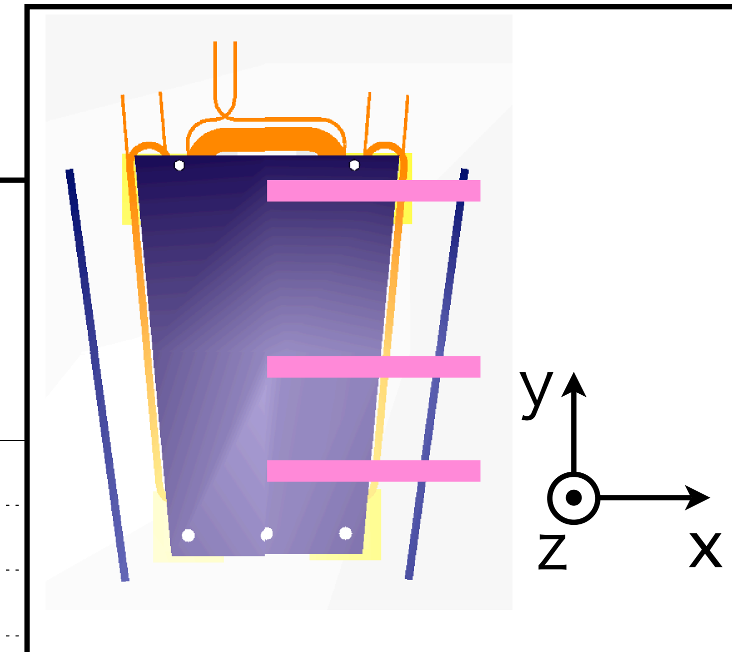
TOSCa vs measurement

On median plane

tosca_vs_meas.kumac

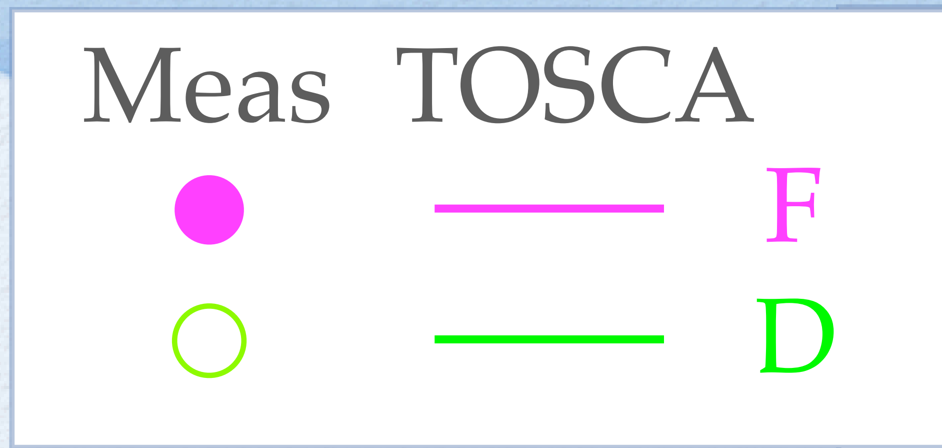


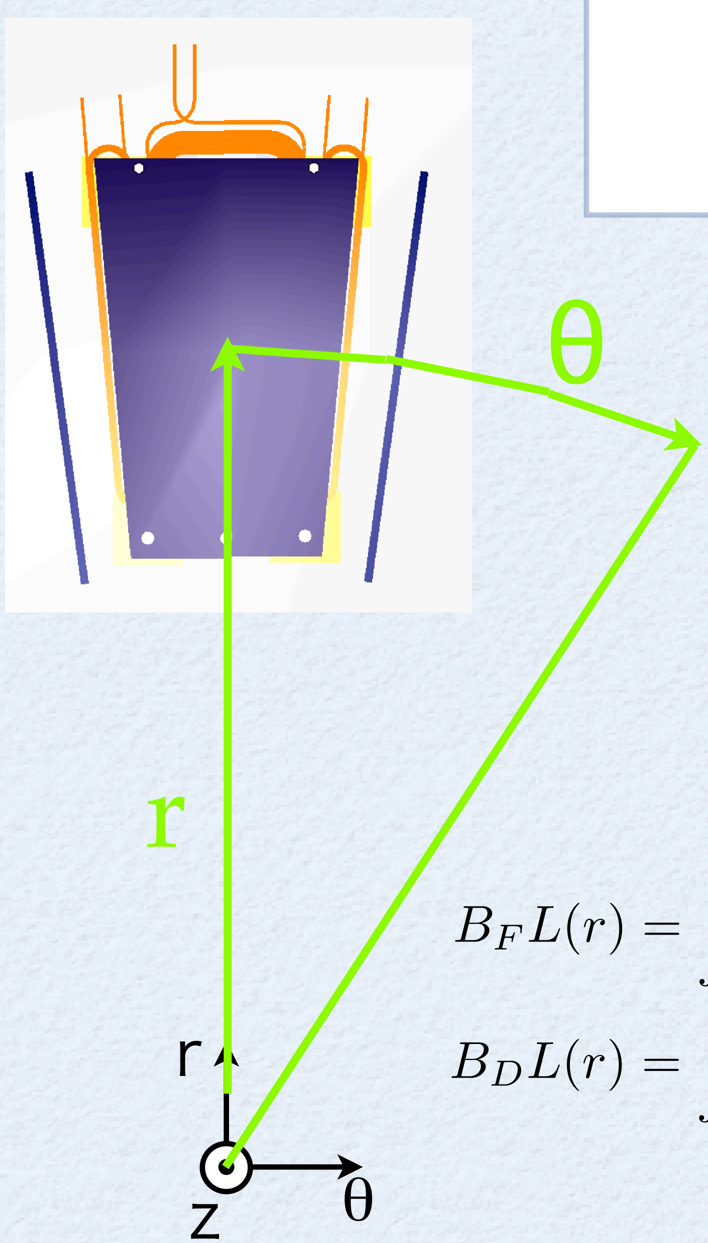




Difference between TOSCA and measurement is about 10 Gauss

BL Integral: @ Median Plane



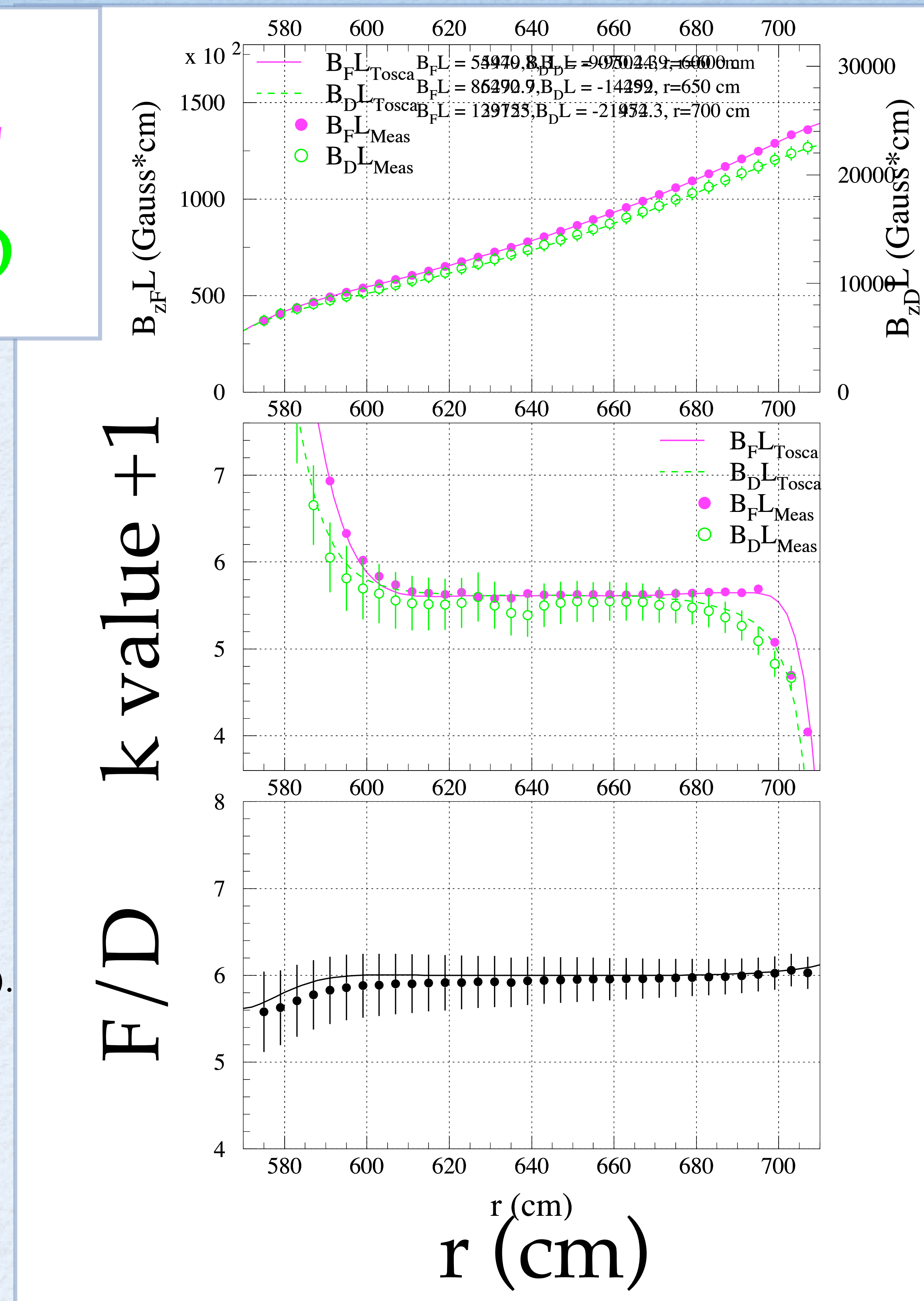


$$B_F L(r) = \int B_z(r)|_{B_z(r)>0} r d\theta \quad \text{(Focus)},$$

$$B_D L(r) = \int B_z(r)|_{B_z(r)<0} r d\theta \quad \text{(Defocus)}.$$

$$k + 1 = \frac{\partial BL(r)}{\partial r} \frac{r}{BL(r)},$$

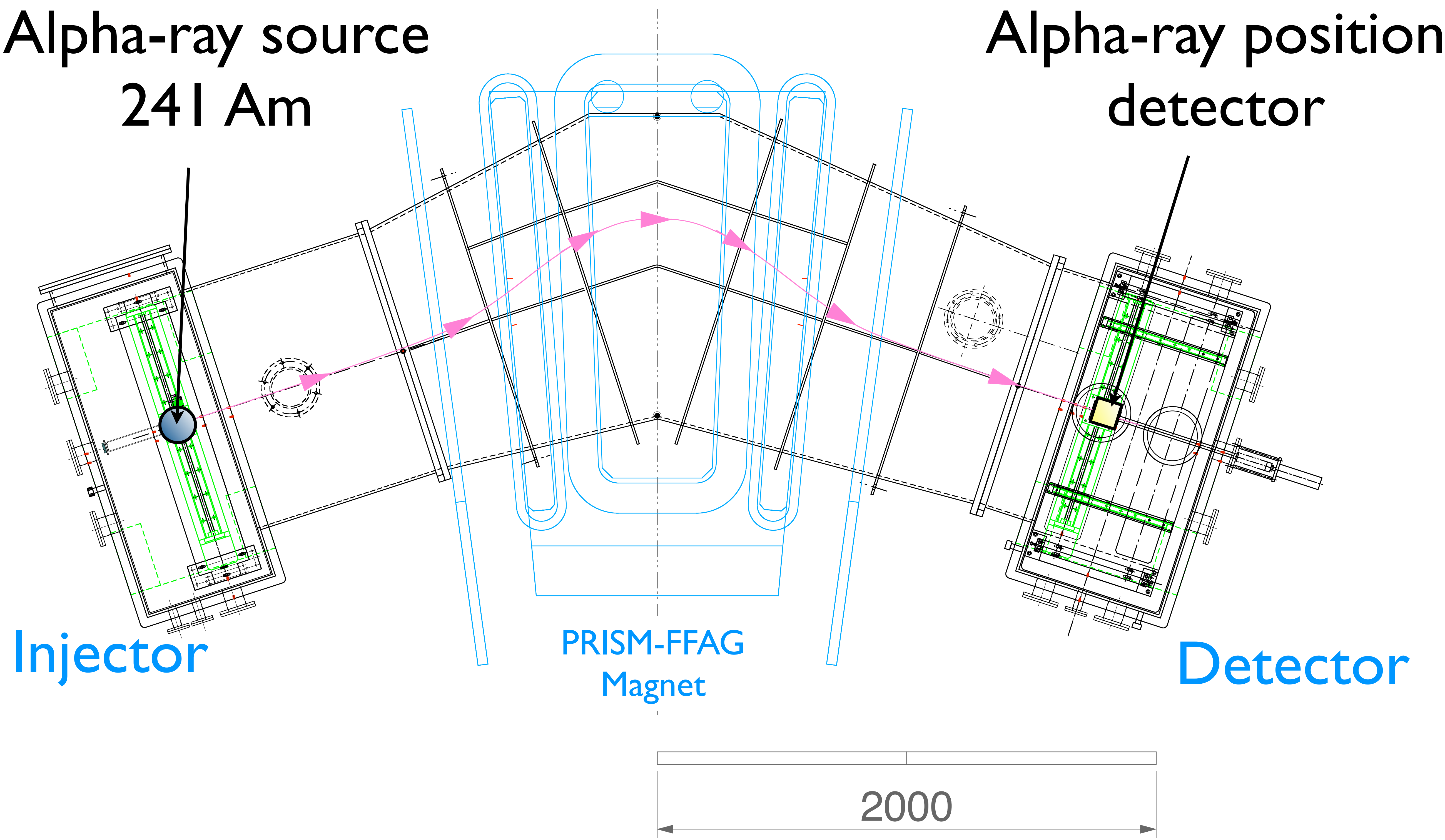
$$F/D = B_F L(r)/B_D L(r).$$



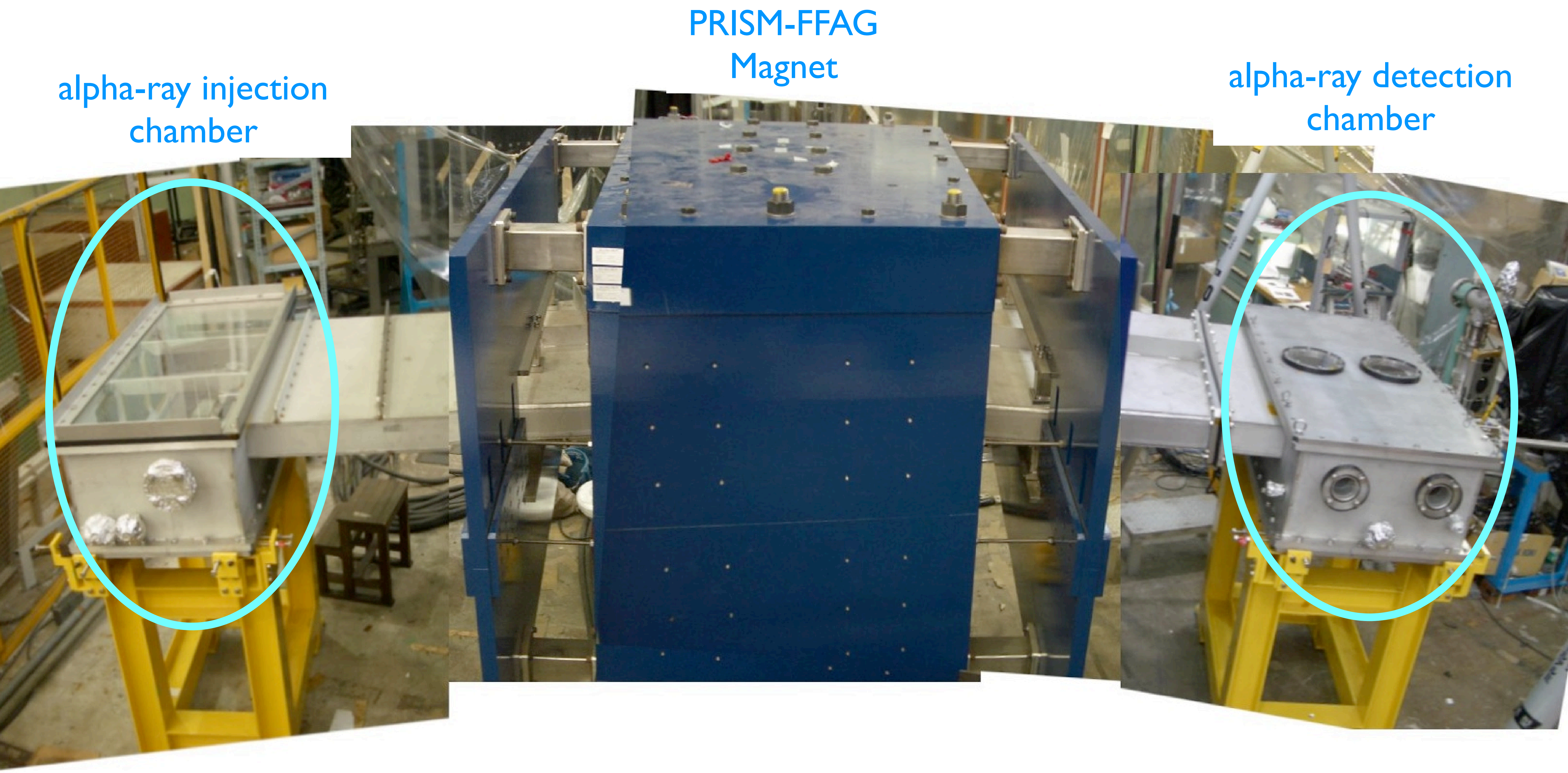
Beam dynamics study with one cell magnet

- Purpose : experimental beam dynamics study at large amplitude = study of non-linear behavior
- Method : determine transfer map from measured phase space of alpha particle at inlet of a magnet and at that of outlet.

Experimental setup

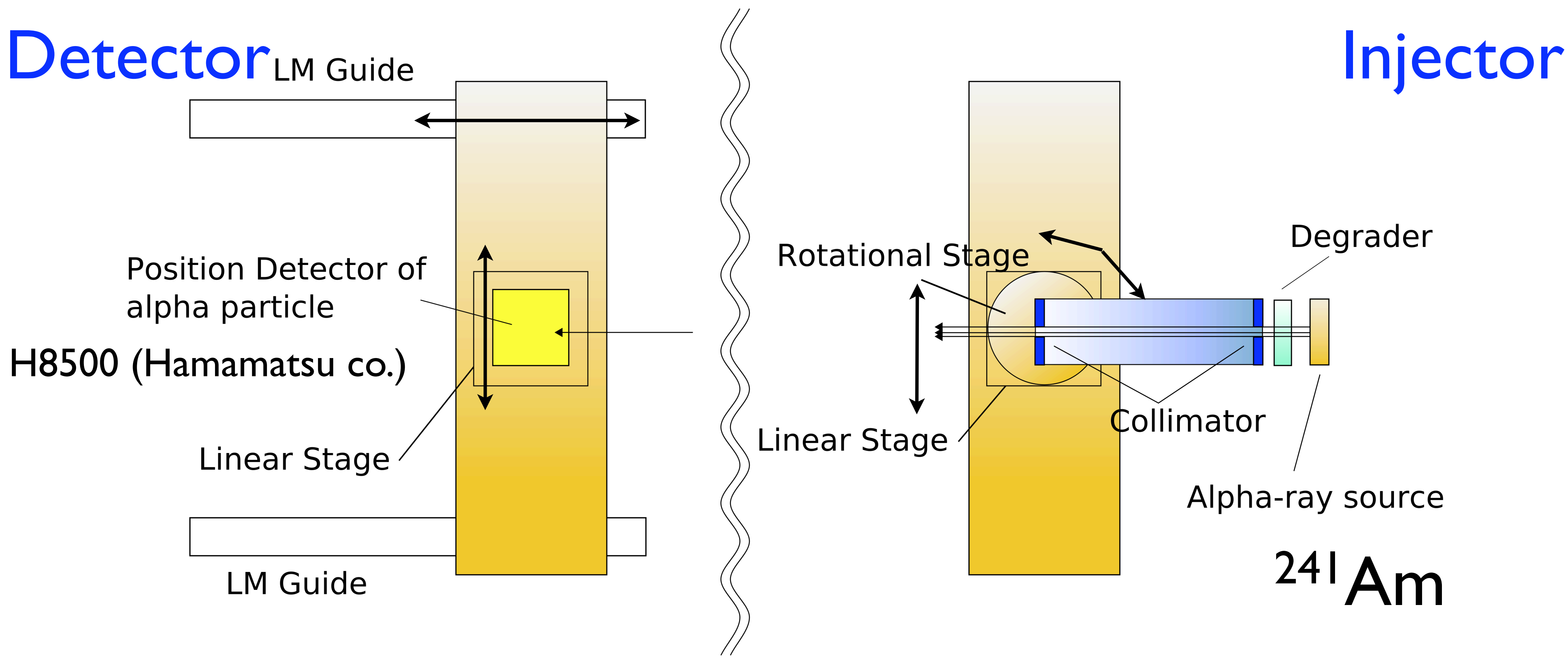


Picture of entire setup



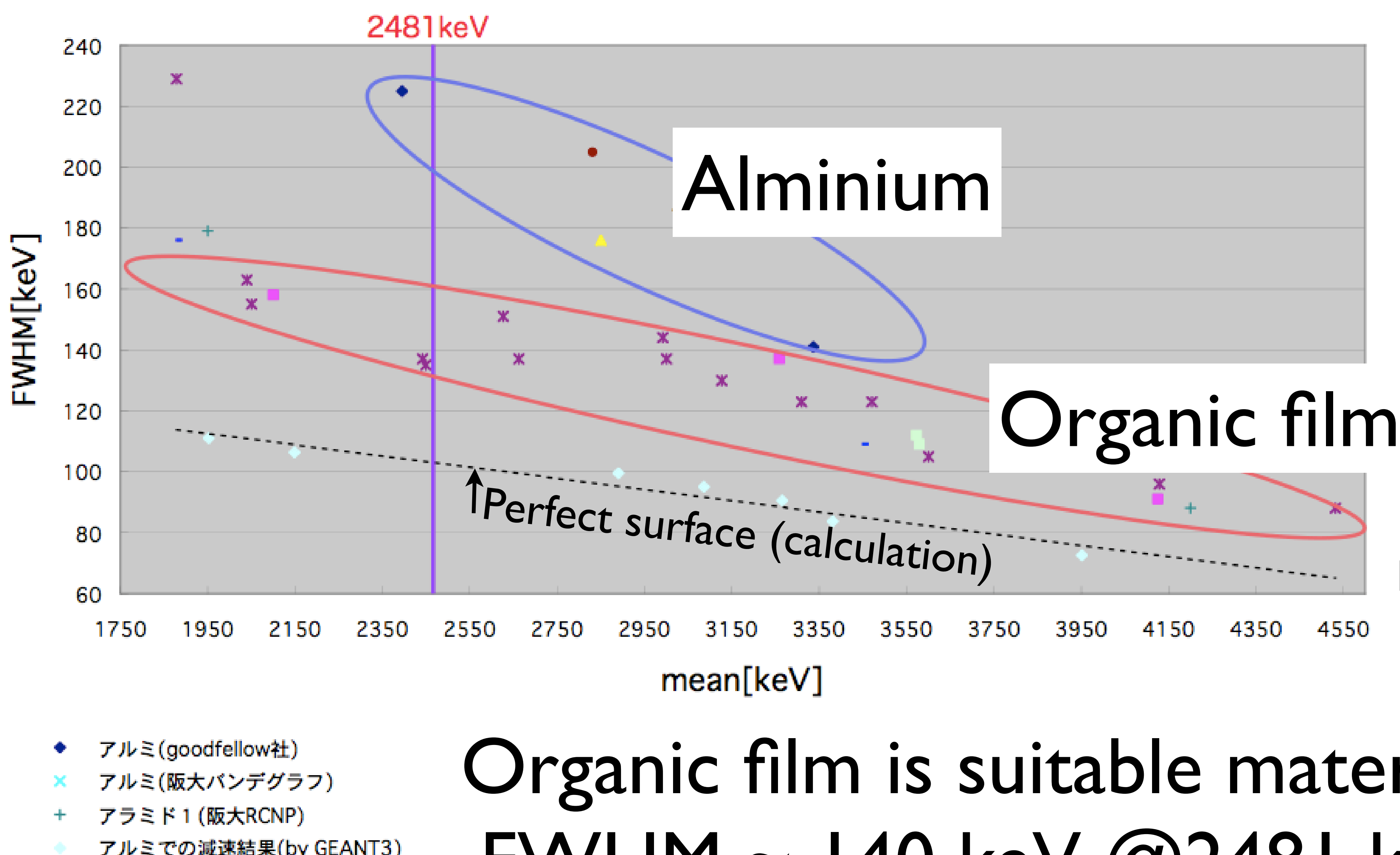
Injector and Detector

- Injector : (x_0, x'_0)
  - Alpha particle emitted from RI(^{241}Am) and degraded by a foil.
  - Angle and position is determined by collimator which is downstream setup to degrader
  - Incident angle and position are changed by stepping-motor-control stages.
- Detector: (x_1, x'_1)
  - Position of alpha particle is measured by position sensitive detector and stepping-motor-control linear stage
  - Angle is determined from measured position difference when detector position is changed in direction of beam axis.



Selection of Degrader

- Energy of alpha particle should be degraded from 5,436 keV to 2,481 keV with thin foil.
- Energy spread greatly change with surface roughness.
- Energy spread has been measured with several material to select good surface material



by S. Araki

Organic film is suitable material!

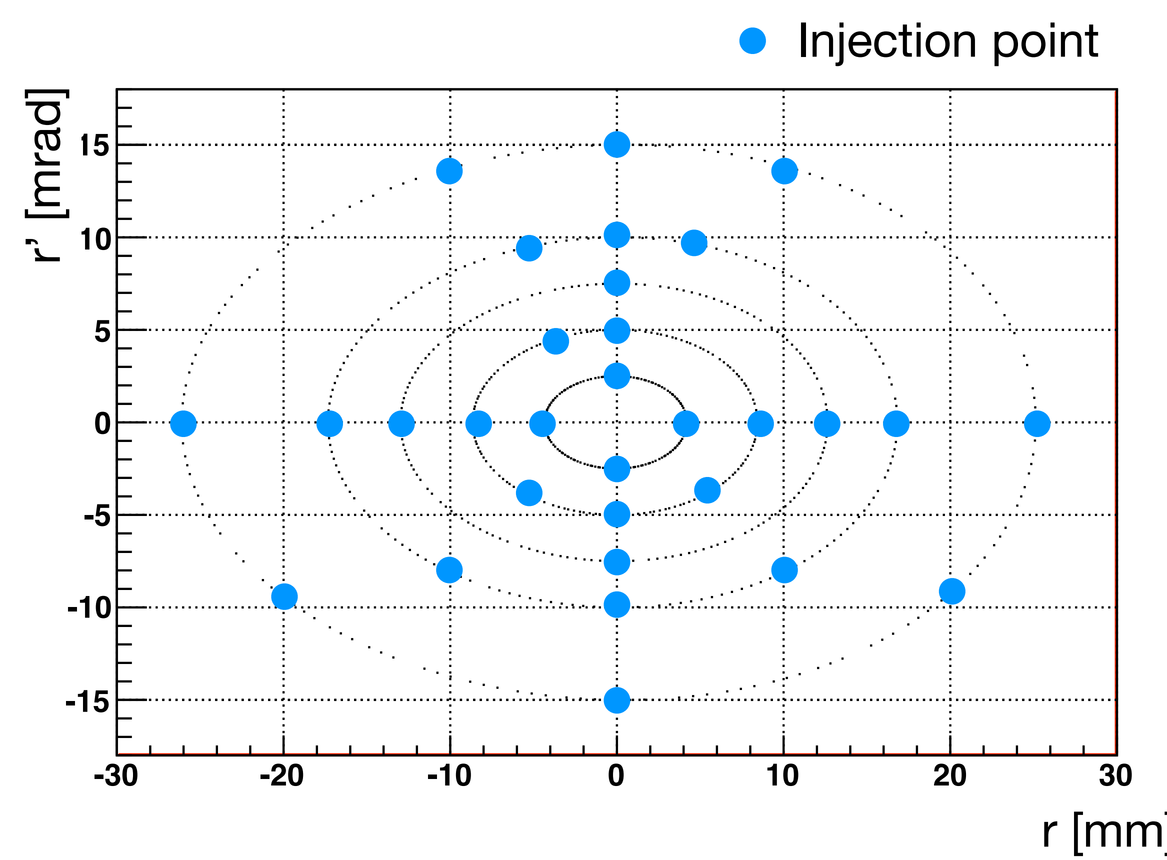
FWHM ~ 140 keV @2481 keV

Equilibrium Orbit & Phase Advance of One Cell

PRISM

- Using the measurement data, relatively amplitude is small
  - calculate one cell 1st. order transfer matrix
  - Least squares method

$$\Sigma\chi_i^2 = \left(\frac{X_i^{meas} - X_i^{cal}}{\sigma_X}\right)^2$$



Using 27 points measurement data...

one cell 1st. order transfer matrix

$$M = \begin{pmatrix} -0.135 & 1.68 \\ -0.588 & -0.112 \end{pmatrix}$$

$$detM = 1.00 \pm 0.05$$

Equilibrium orbit

$$r_0 = 6189.7 \pm 0.3[mm]$$

$$r_0' = -0.9 \pm 0.2[mrad]$$

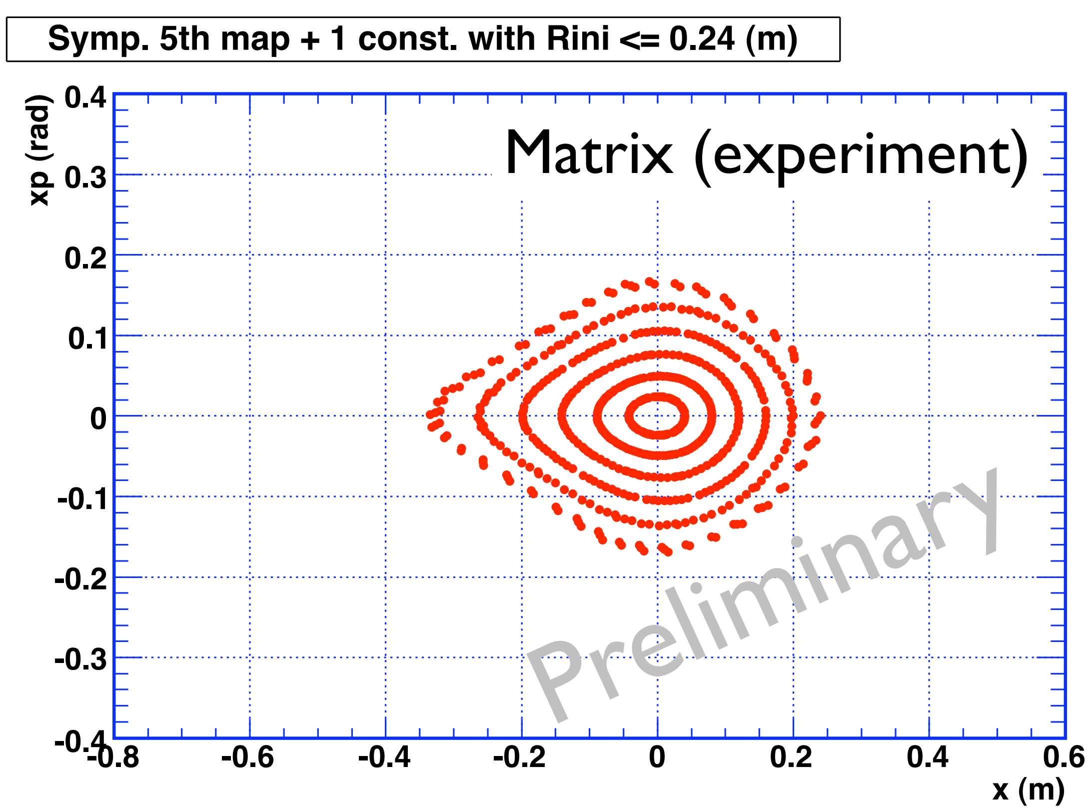
Tune

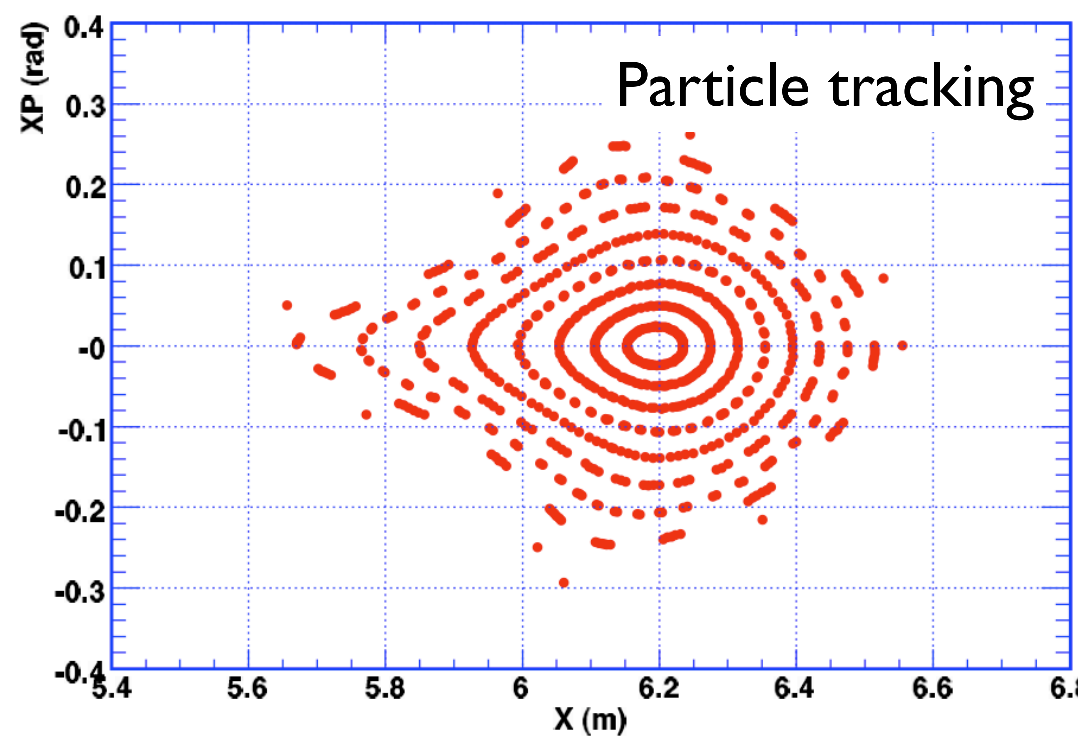
$$\nu_{meas} = 2.70 \pm 0.07$$

$$\nu_{sim} = 2.741$$

Truncated Taylor Map

- Truncated taylor map of the magnet transport matrix is obtained. The order is 5 th order.
- The particle motion on phase space successfully reproduce particle tracking simulation with TOSCA +ZGOUBI simulation results.

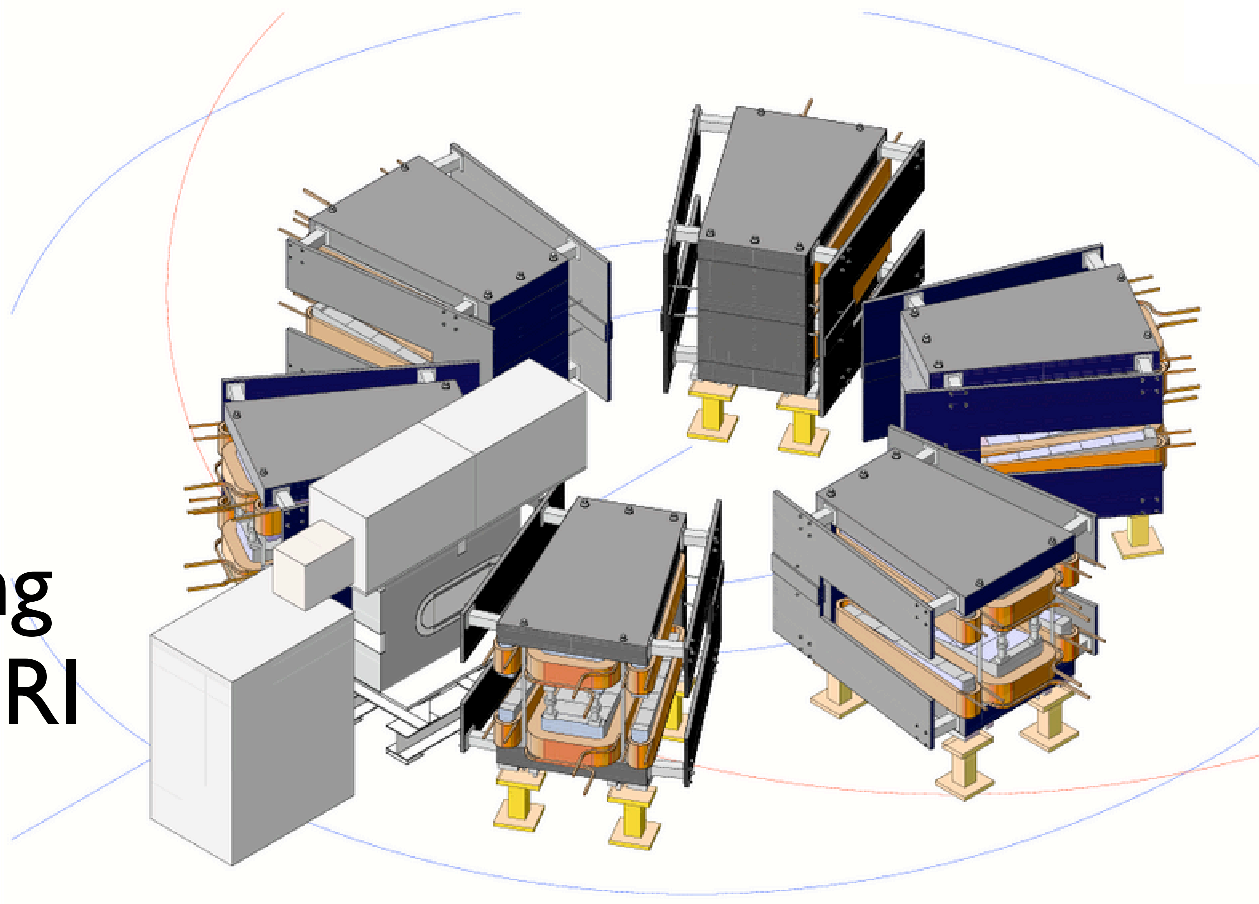




Six cell ring study

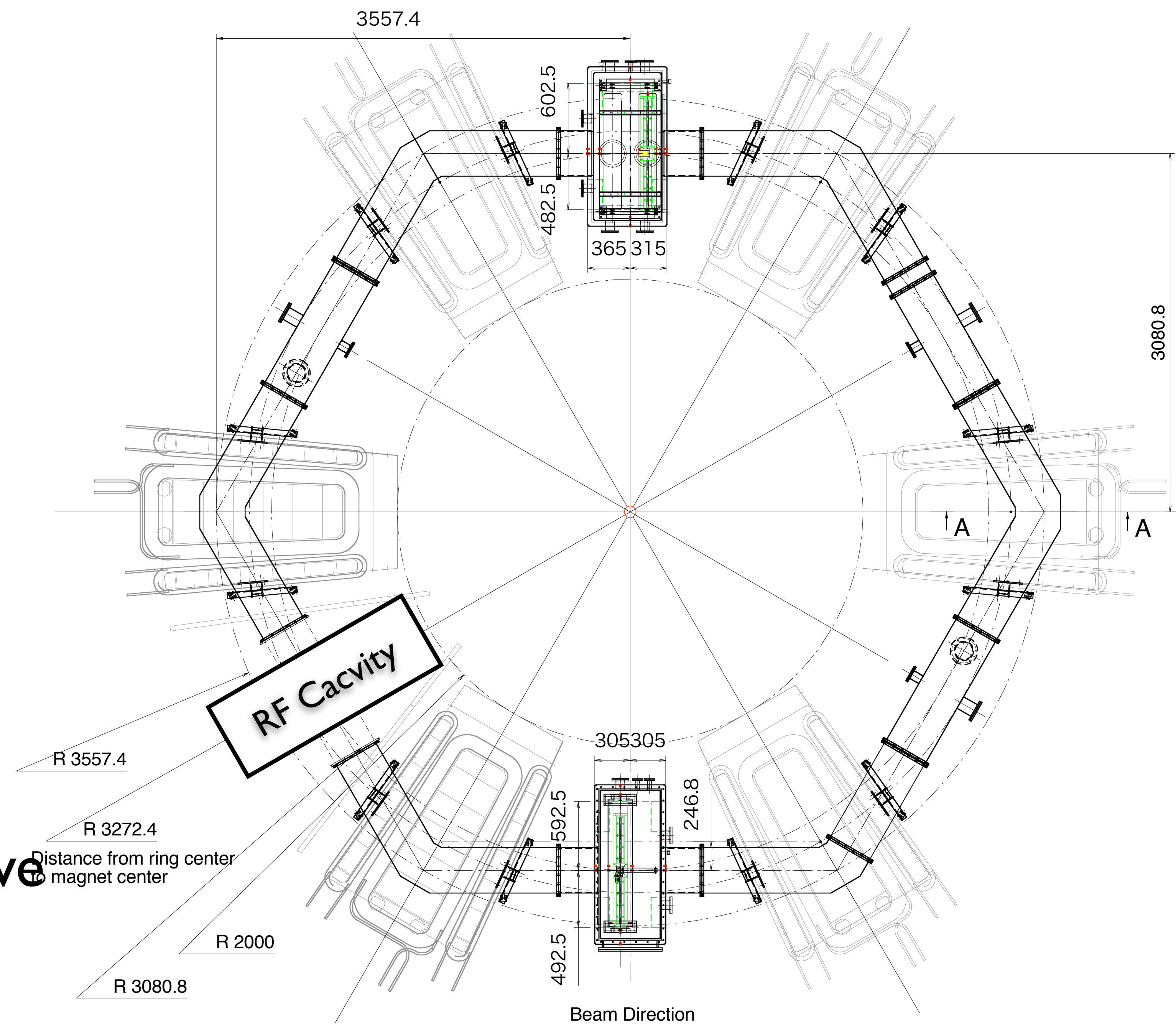
Six cell ring

- Full scale of PRISM-FFAG is 10 cell. But, we will start with scale down ring of six cell due to budget limitation.
- Purpose of comissioning with six cell :
  - Beam orbit study
  - Phase rotation
  - Establishment of comissioning method with alpha ray from RI source.



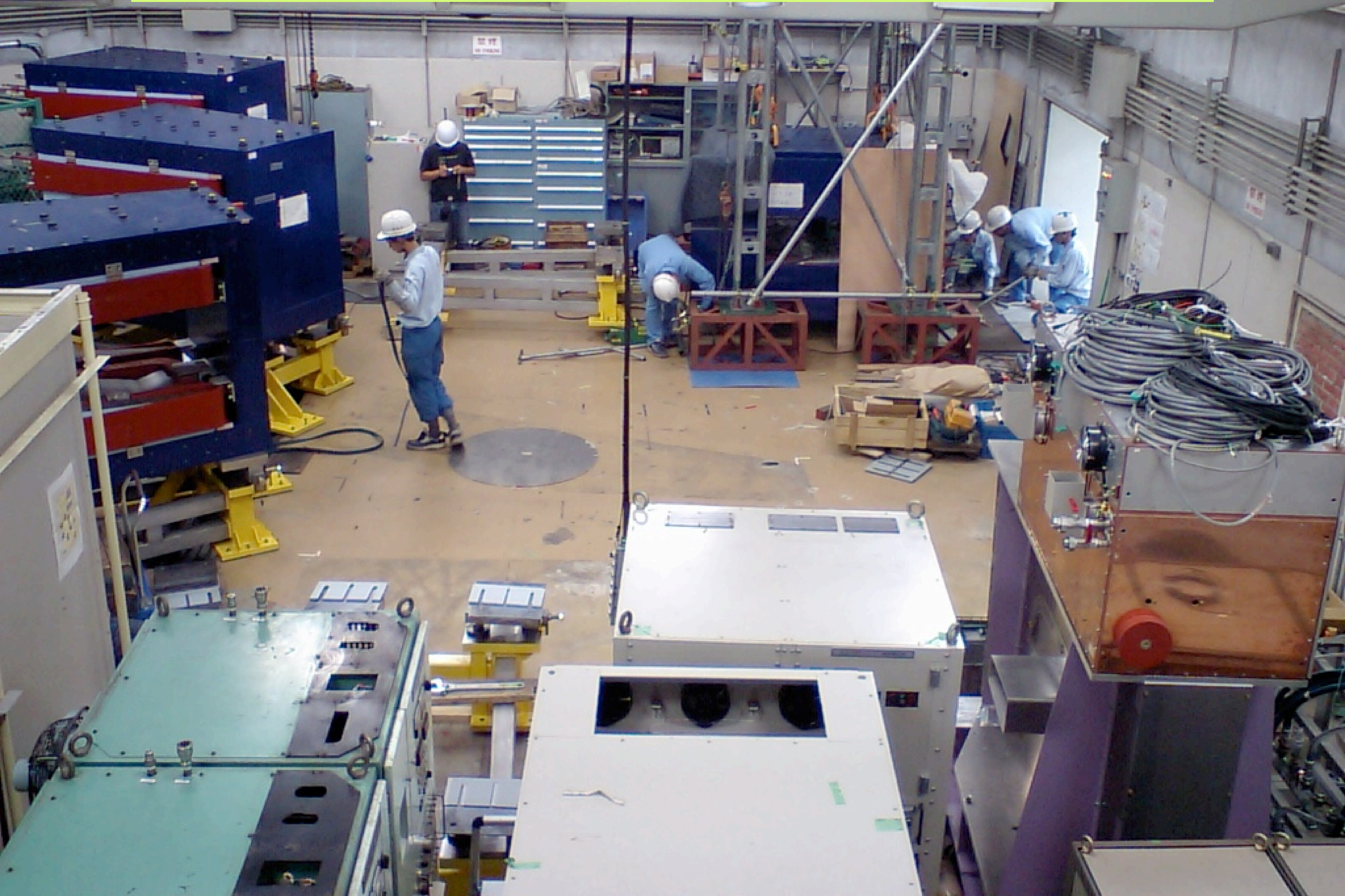
Commissioning of six cell

- Construction of 6 cell ring.
  - Installation of six magnets
  - Magnet alignment
  - Beam duct install.
- Detector development
  - Precise position monitor
  - Energy monitor
- Kicker system of alpha particle
- Generation of Sawtooth RF wave



Comissioning of six cell ring started at sep. 2007

Construction of six cell ring



Construction of six cell ring

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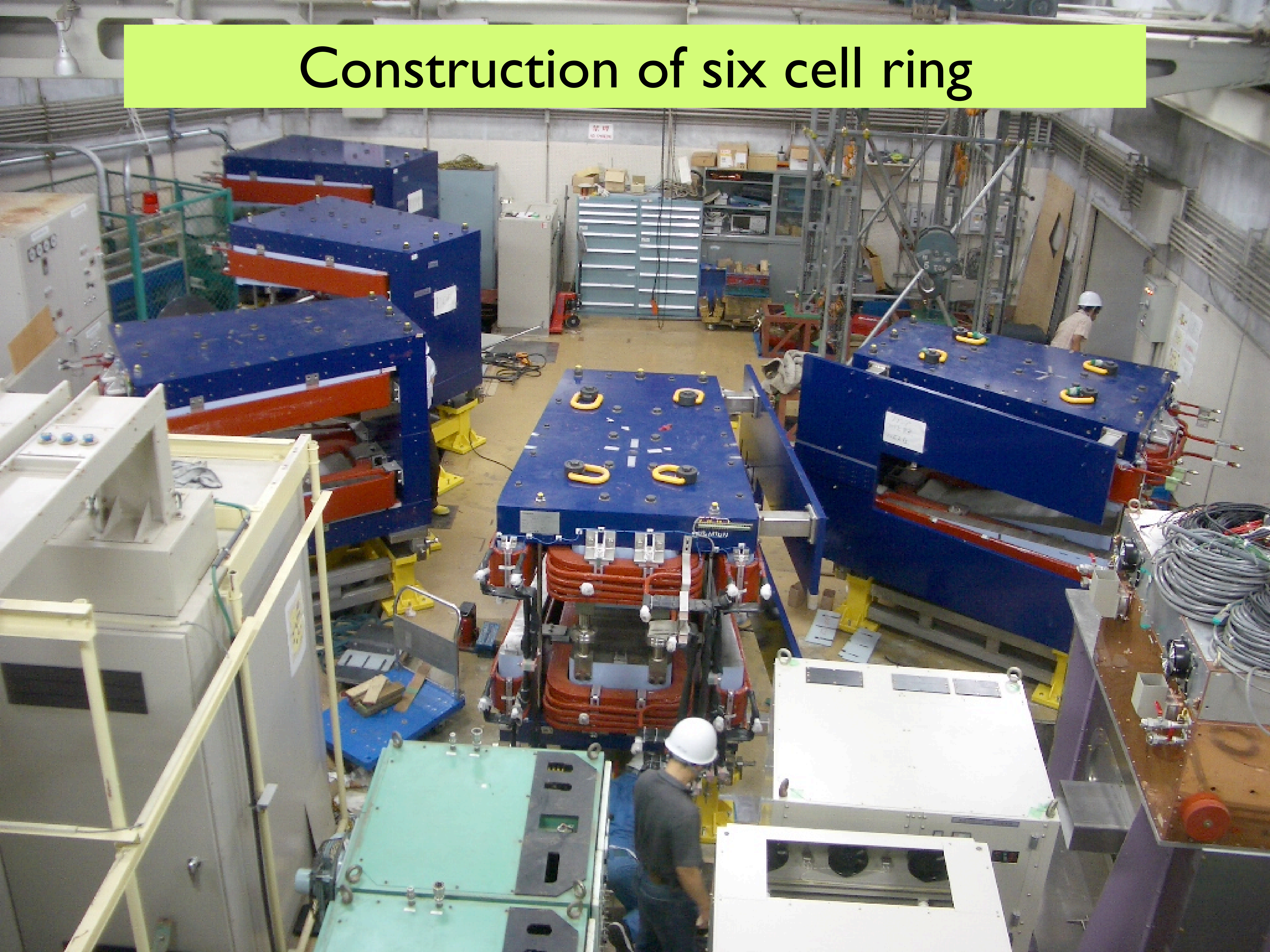
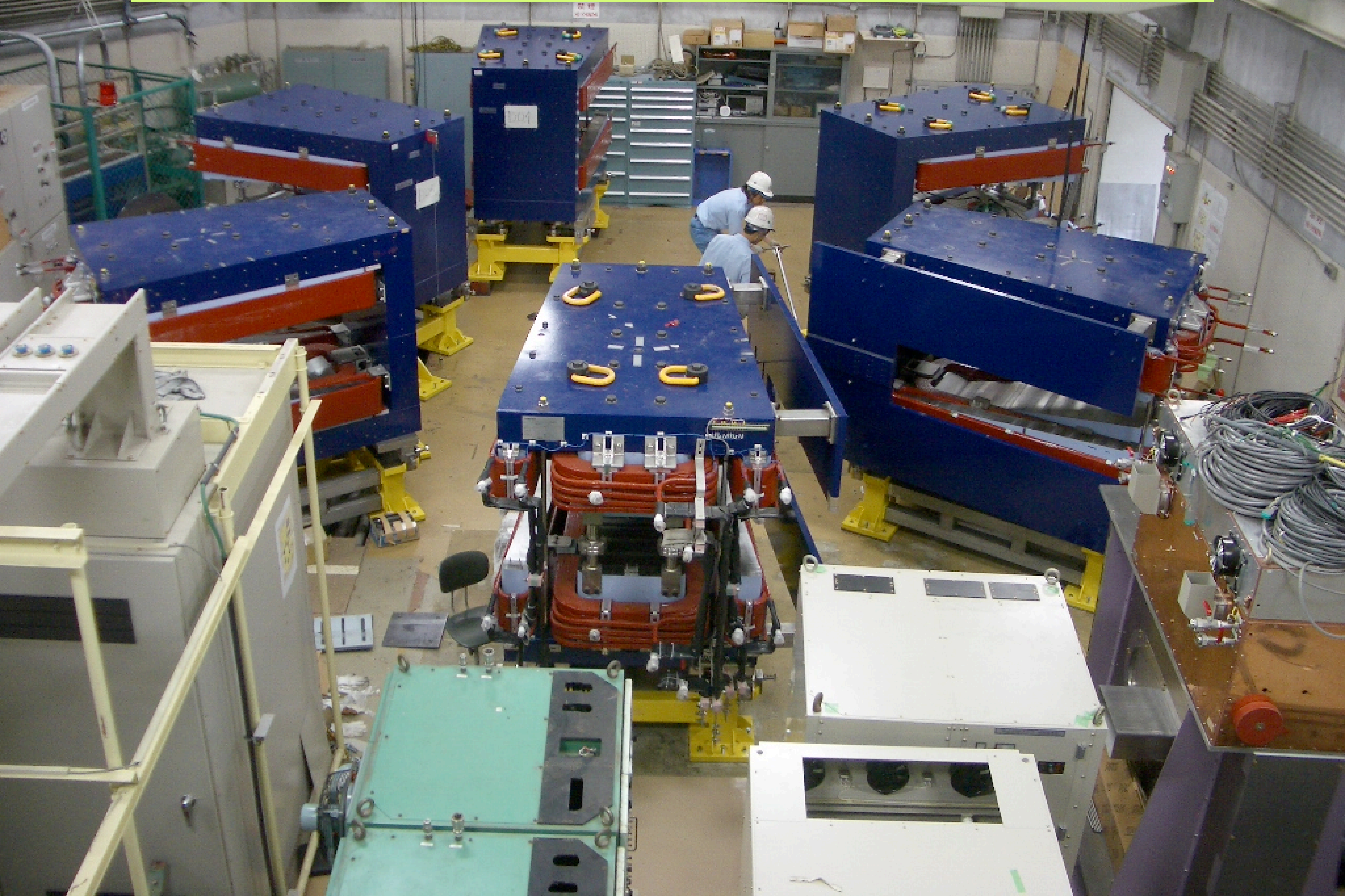
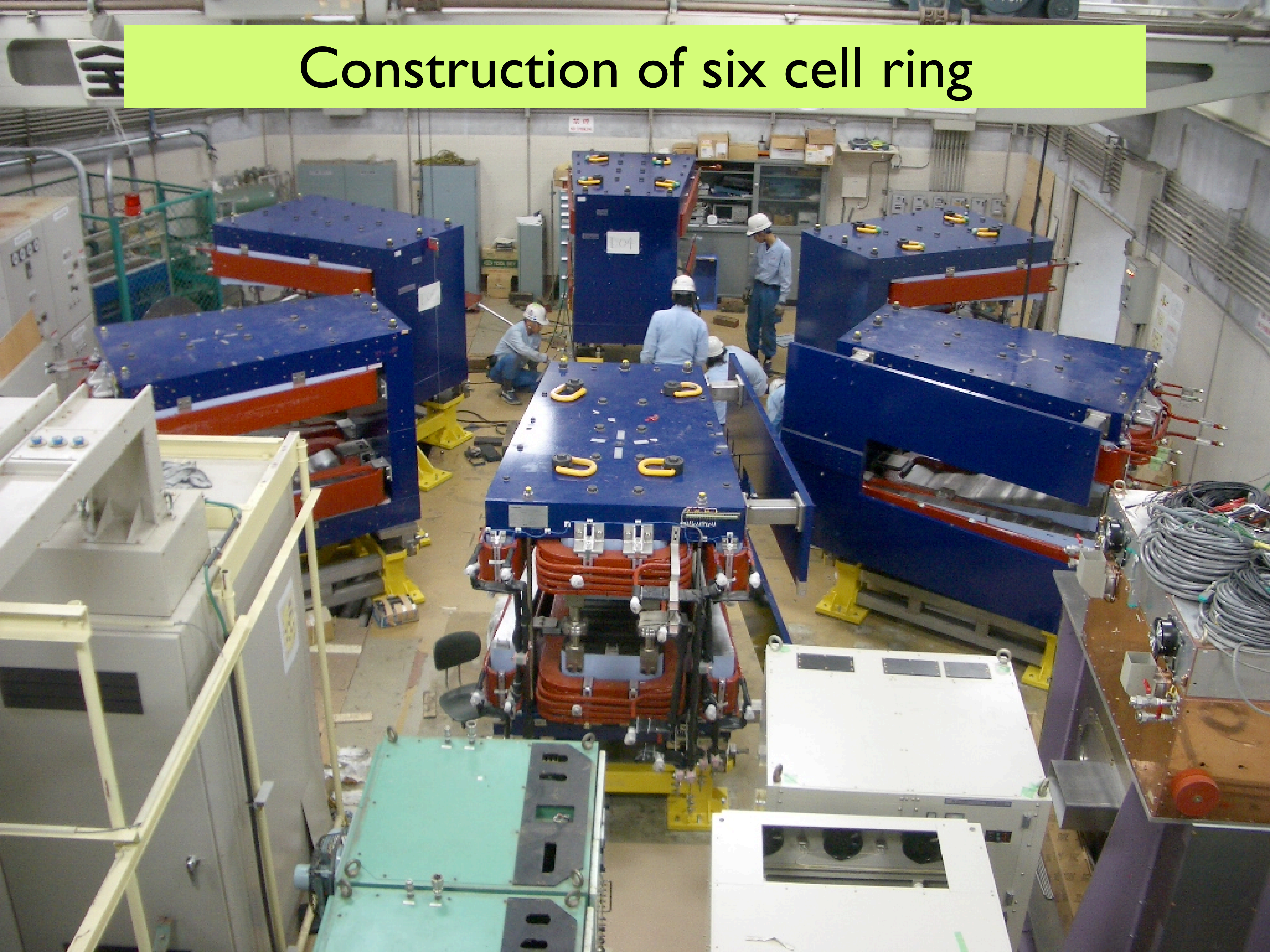


Construction of six cell ring



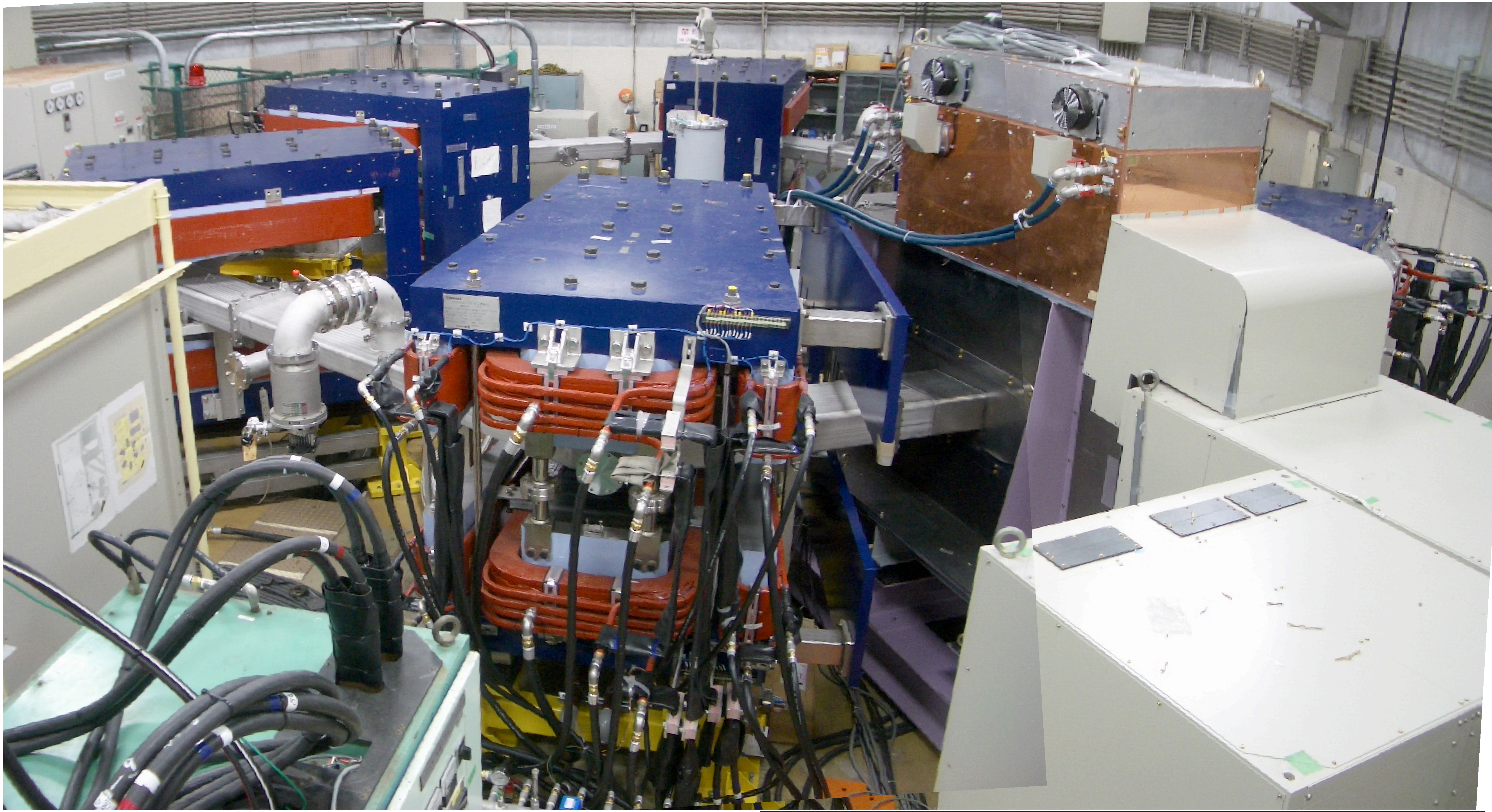
Construction of six cell ring



Construction of six cell ring

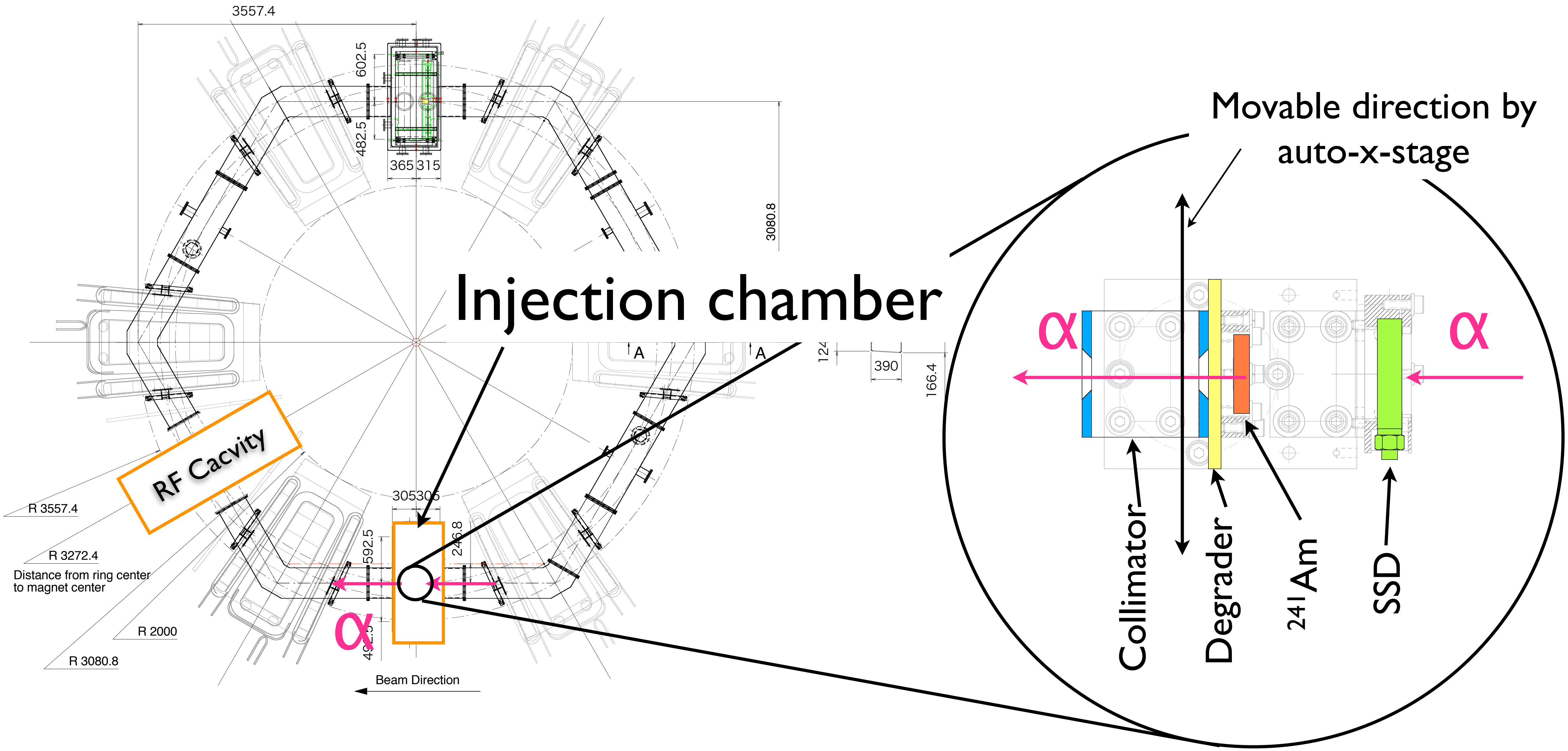
Recent picture of six cell FFAG ring

PRISM



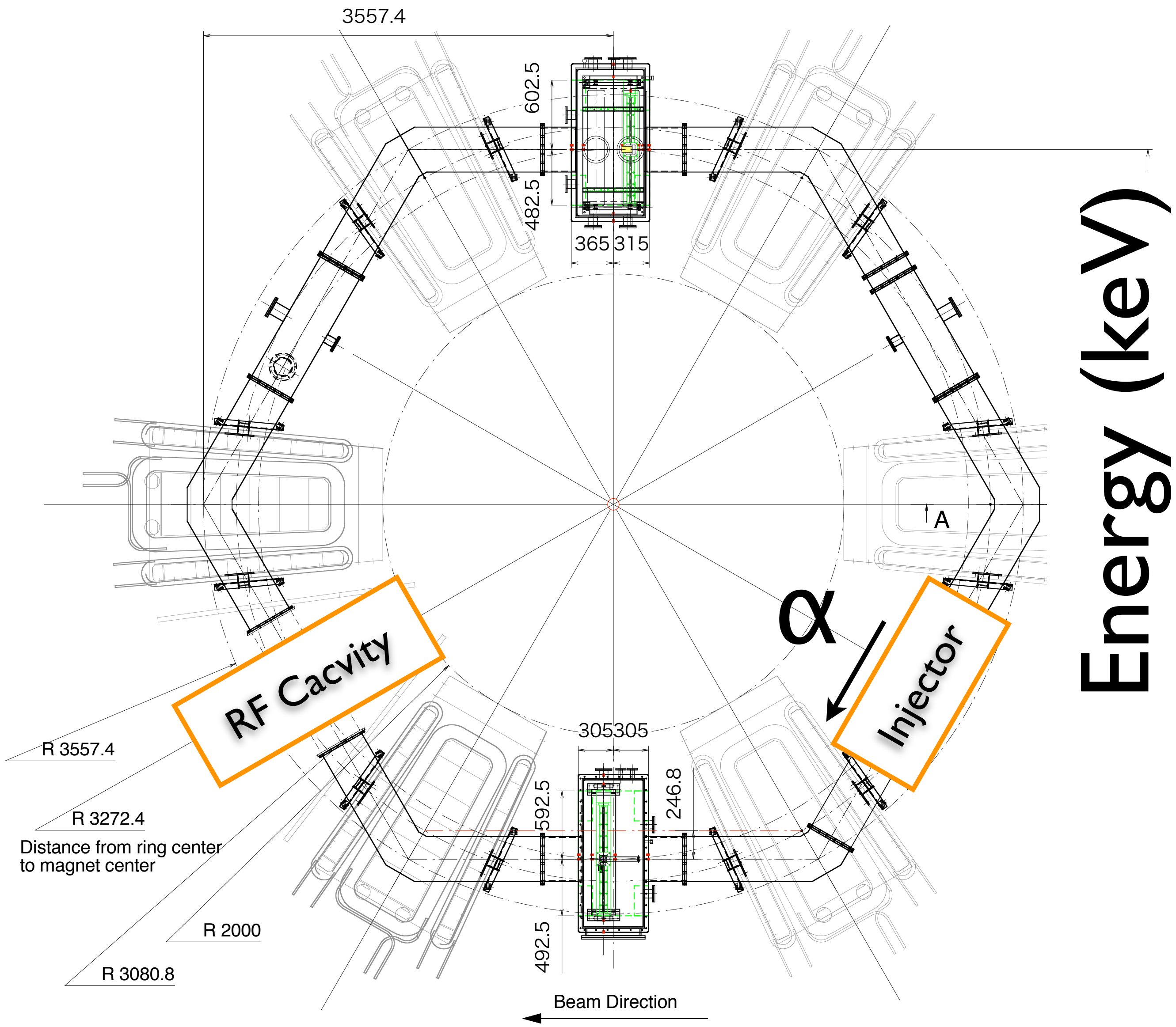
- Beam duct installation finished.
- Alignment has been finished.
- Magnet excitation test has been finished.

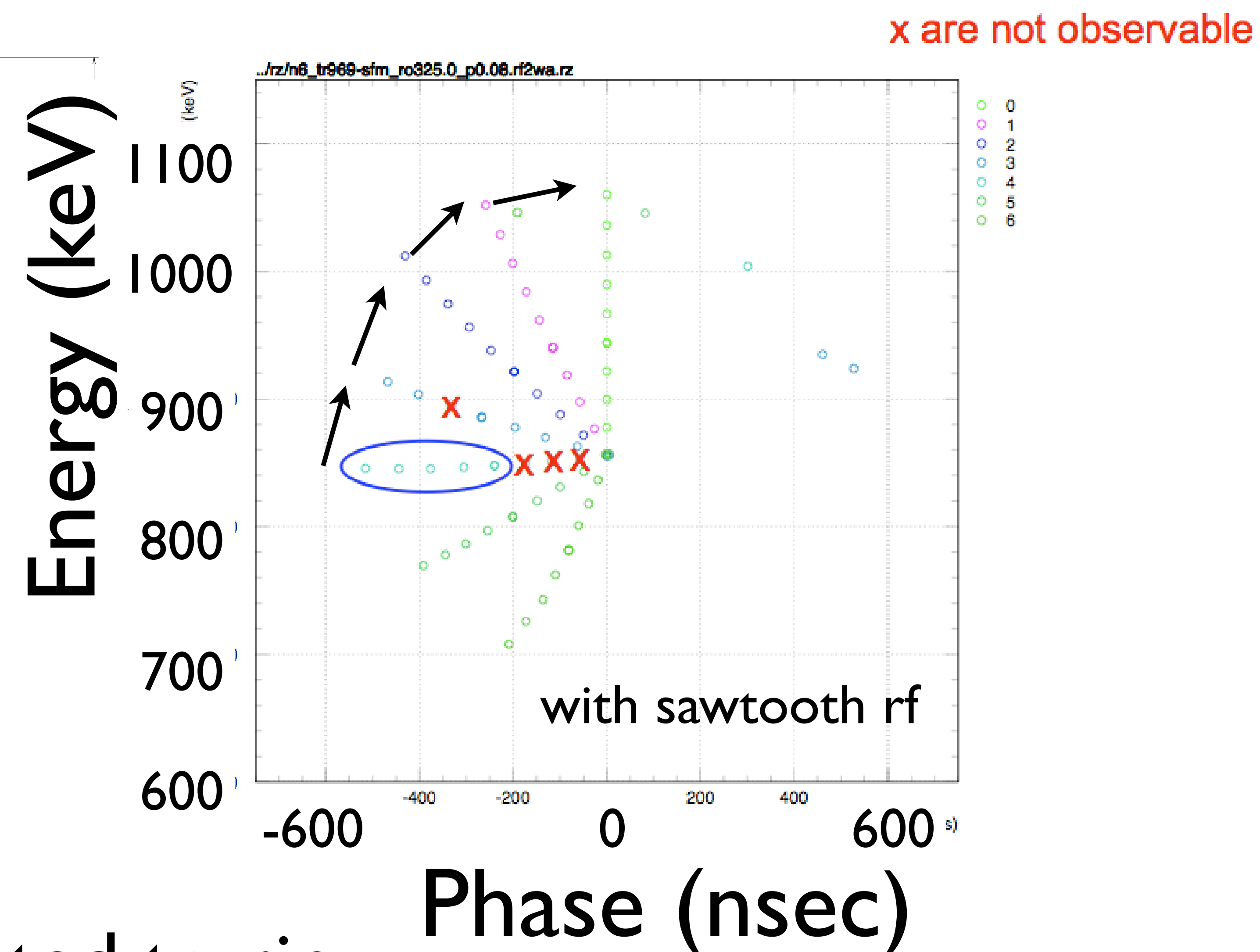
How to measure closed orbit



- DC alpha particle injected to ring.
- α beam can rotate one turn and detected by SSD.
- Collimator can determine initial angle and position of alpha particle.
- Closed orbit can search by moving collimator and SSD on auto-x-stage.

How to measure phase rotation





- Pulsed alpha particle injected to ring
- α beam can rotate several turn deviating from detector with betatron oscillation
- α beam incident to SSD after a few turn, energy and time of Flight is measured by SSD.

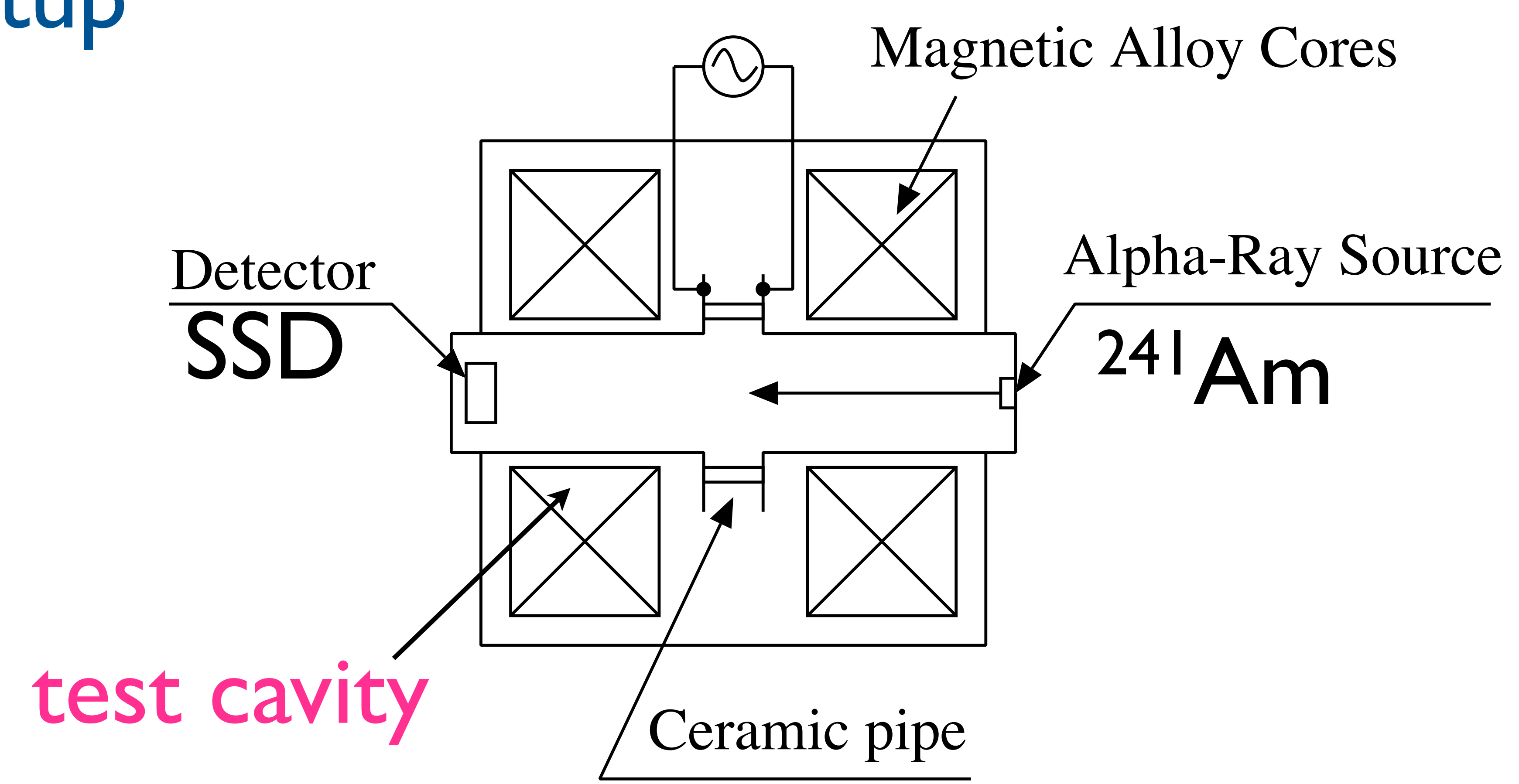
Beam monitor

- SSD
  - Measurement of energy
  - Coarse position monitor
  - More than one turn
- Scintillation counter
  - Fine position monitor
  - Less than one turn

SSD (Solid State Detector)

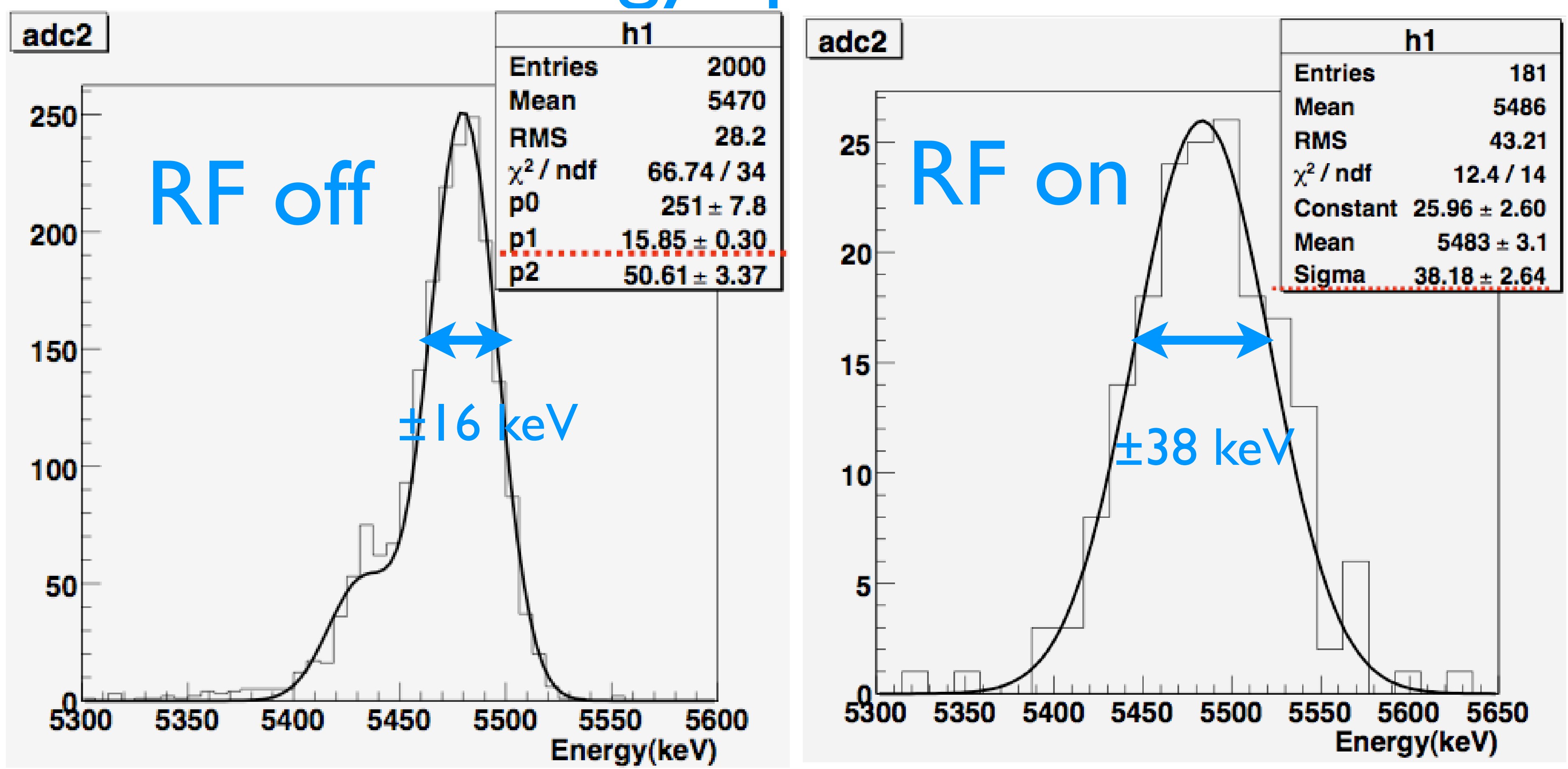
- SSD is used to measure energy of alpha particle.
  - Effect of noise from RF Field to SSD.
    - ✲ Energy resolution of ~50 keV is required while RF power is turned on.

Setup



Energy resolution of SSD

Energy spectrum



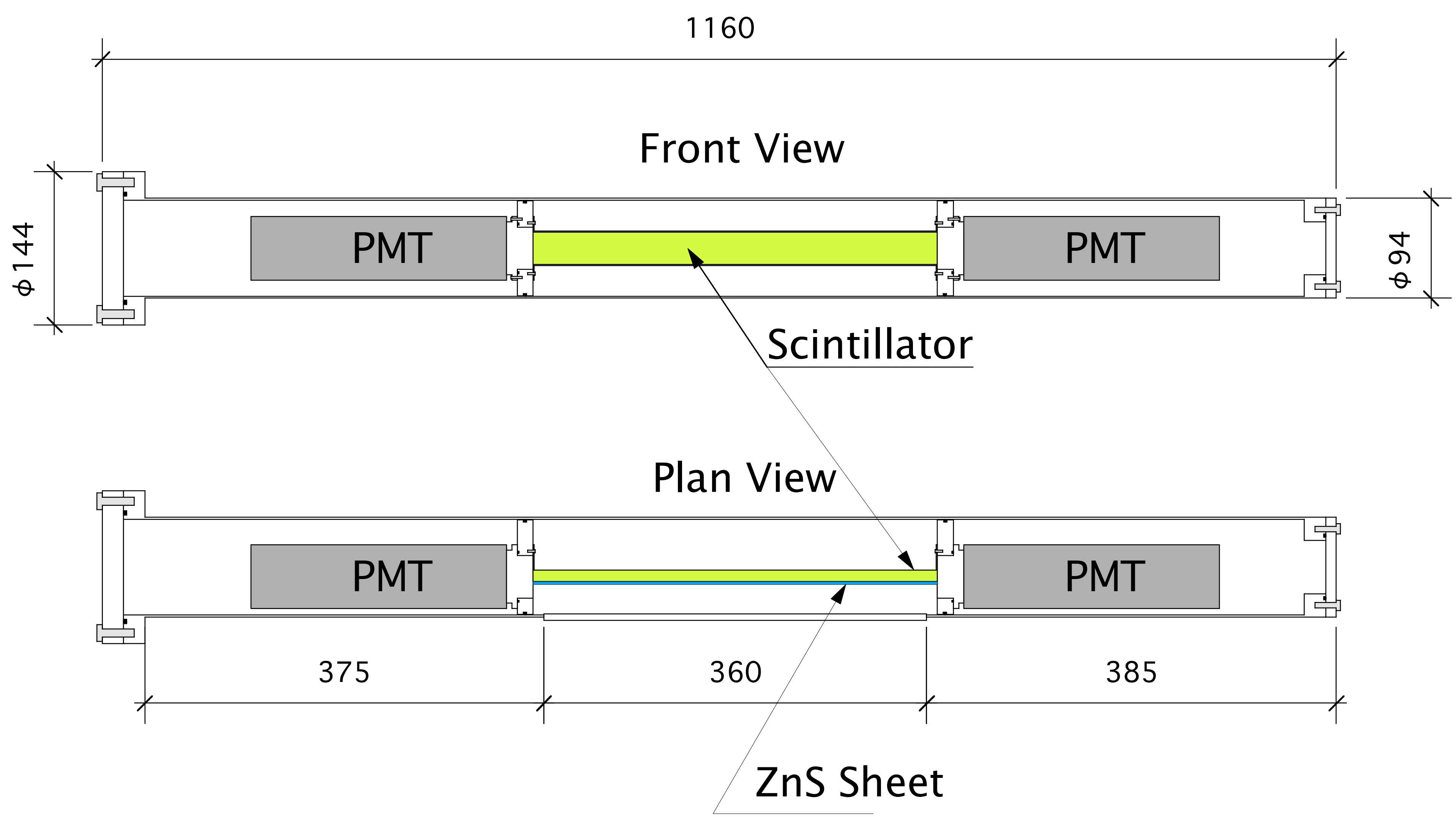
by Y. Eguchi

- Energy resolution of 38 keV is achieved with RF on.

This energy resolution is sufficiently good.
In 6 cell experiment, detector will be located farther away from RF cavity than this experiment. The energy resolution become smaller than this value.

Position Monitor

- Position Monitor is used to measure beam center.
- Phoswitch type.
  - ZnS sheet + Scintillator



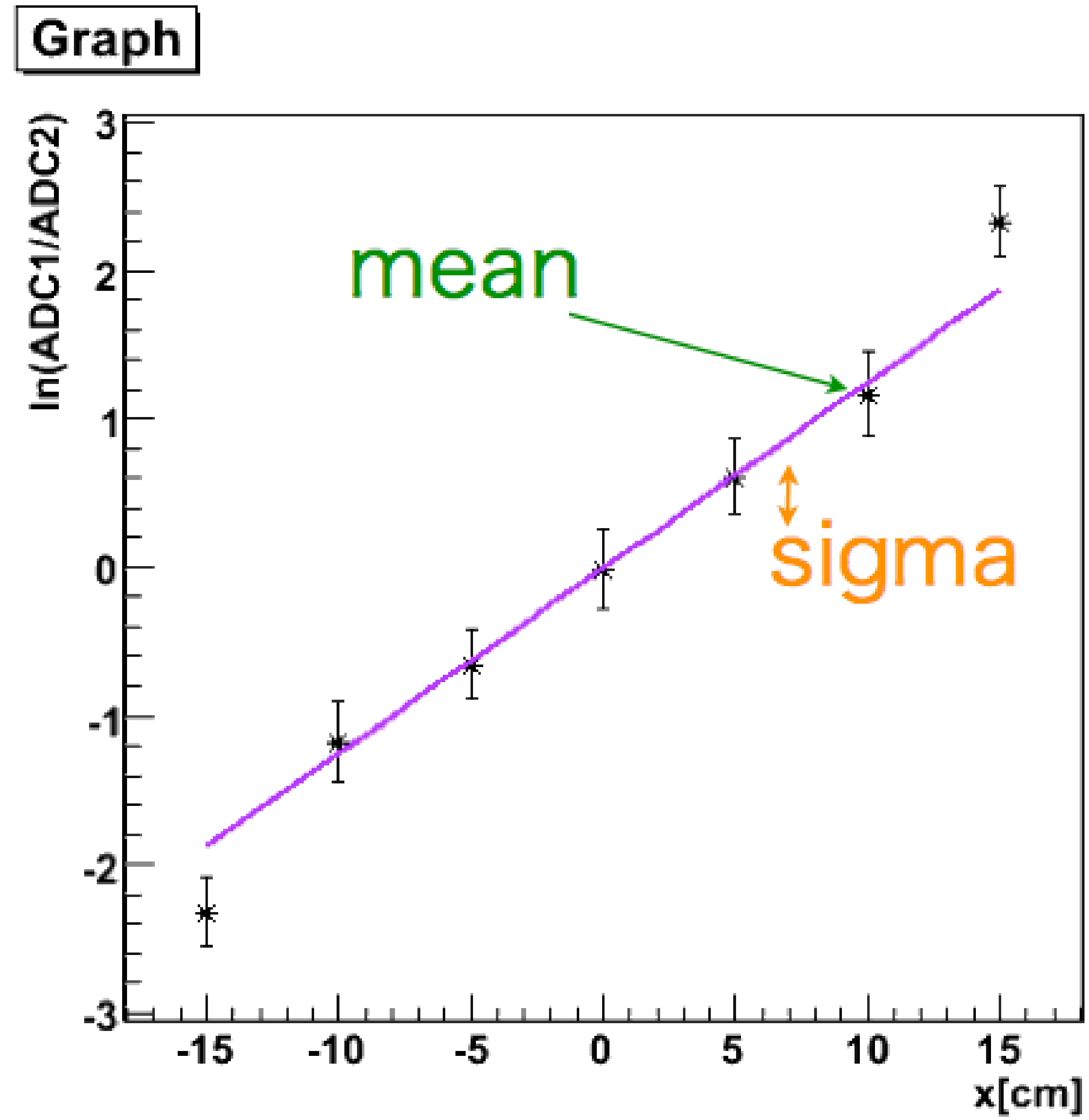
Position Resolution

- Position Resolution Measured by Collimated 241Am Source

- Position Resolution

  - +- 2 cm : one alpha particle

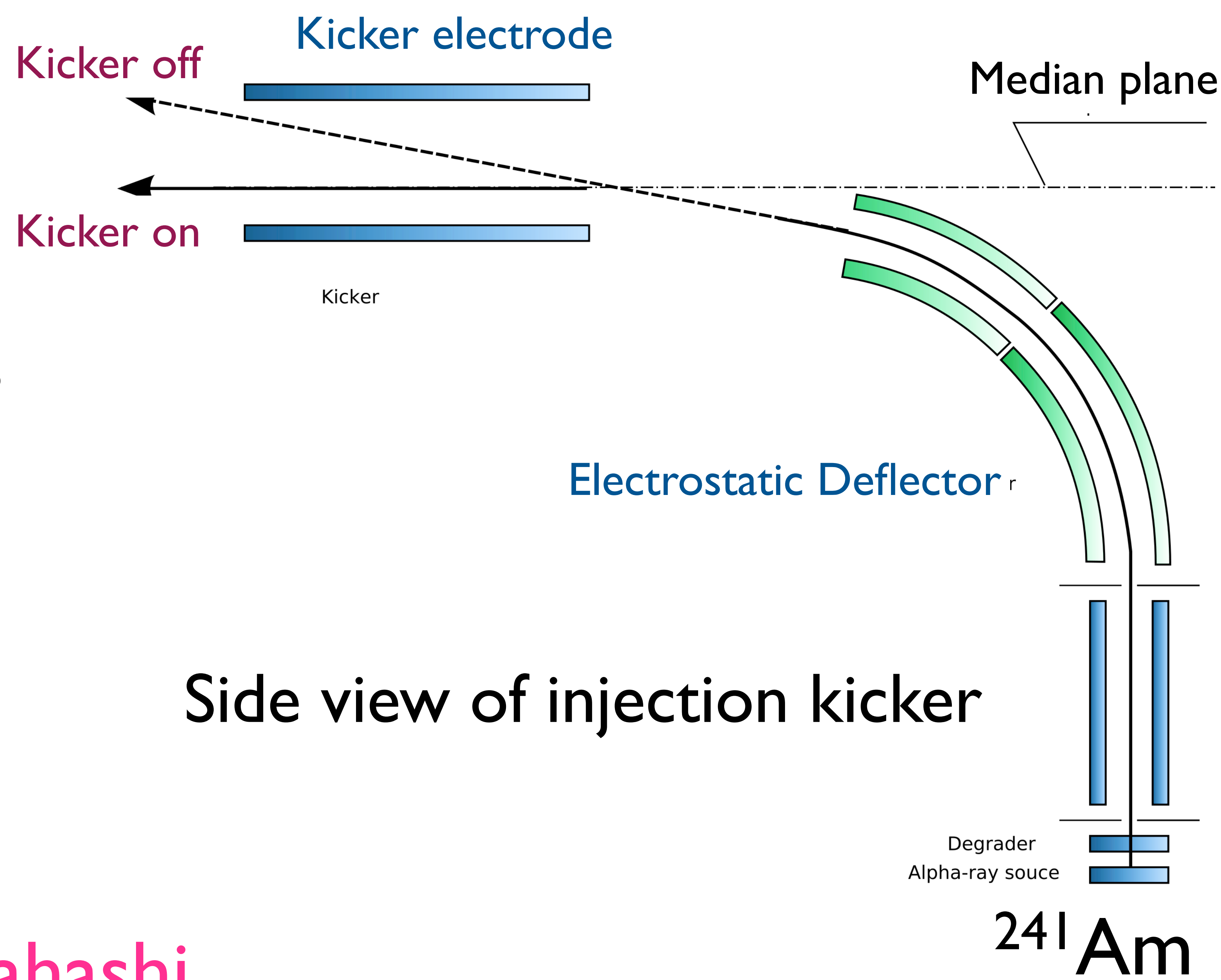
  - +- 0.2 cm : beam center



$$ln\frac{I_1}{I_2} = \frac{2}{\lambda}x + ln\frac{I_{01}}{I_{02}}$$

Alpha-ray injector to 6 cell ring

- Pulsed beam is required to observe phase rotation
- Pulsed beam
  - with electrostatic kicker
  - Electrode will be install to RF acceleration test apparatus
- Vertical injection



Side view of injection kicker

Talk by Dr. Itahashi

Schedule of six cell comissioning

- Construction of Six cell FFAG ring : Finished
  - Installation of magnets
  - Installation of beam duct
  - Wiring of magnet coil
  - Alignment of magnets
  - Excitation of six magnets
- Measurement of closed orbit : March. 2008
- Generation of Sawtooth RF : Mar. 2008
- Production and instllation of kicker system : Apr. 2008
- Measurement of phase-space rotation : May. 2008

Summary

- PRISM is muon facility to provide high intense and high brightness muon beam aiming at searching for μ-e conversion process which is LFV of charged lepton.
- Phase-space rotation technique is used to make muon beam of narrow energy width.
- Scaling FFAG is adopted as phase rotater.
- Designed for PRISM-FFAG ring has been finished.
- Comissioning of six cell ring is now underway.